THE 'ENGLISH ELECTRIC' JOURNAL

VOLUME FIFTEEN NUMBER FIVE MARCH 1958

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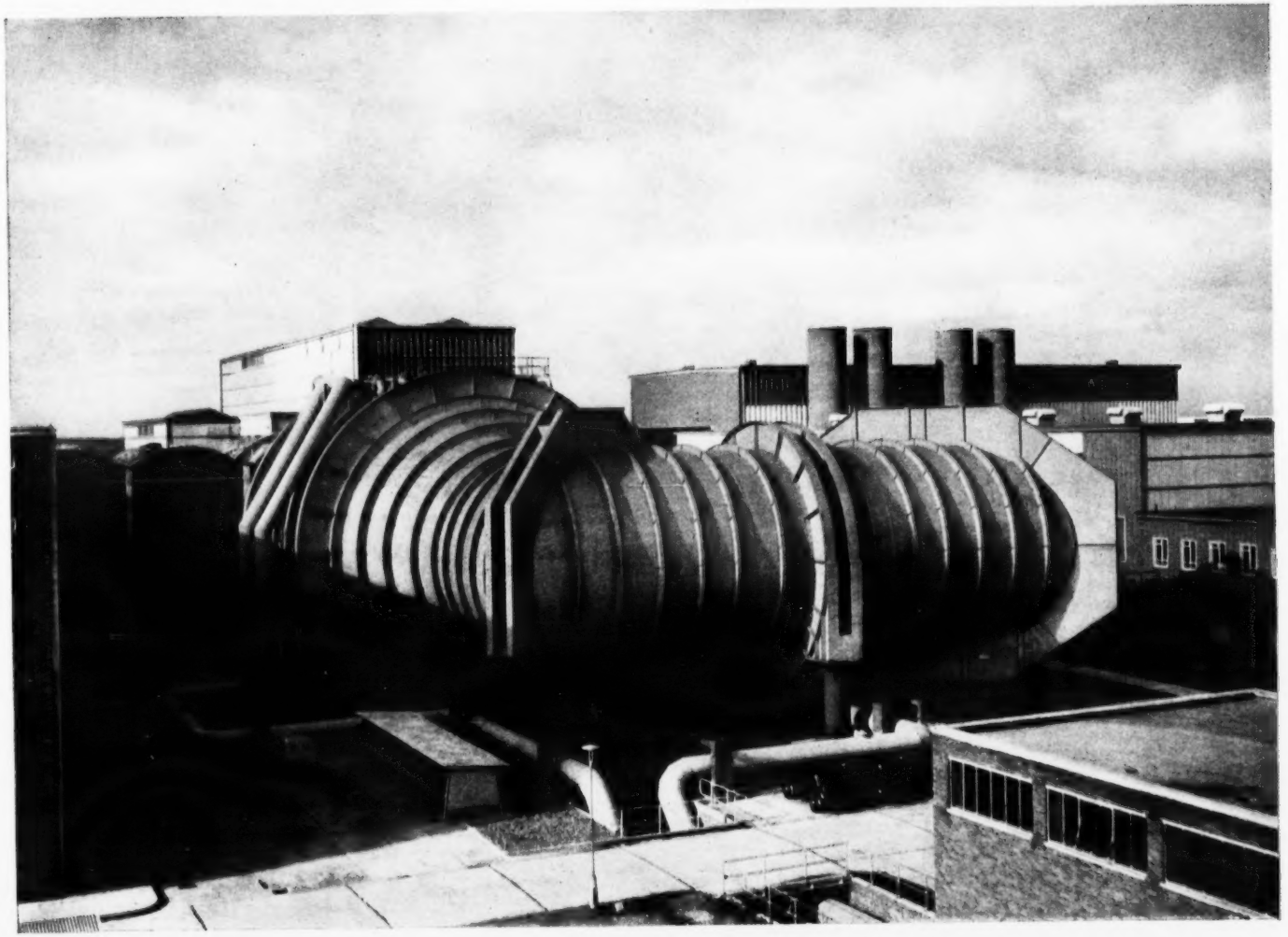

The 8 ft × 8 ft high-speed wind tunnel circuit at the Royal Aircraft Establishment, Bedford

Wind Tunnel Drives for the Royal Aircraft Establishment at Bedford

By W. E. STREETE, A.R.Ae.S., Assoc.I.E.E.

In the December 1950 issue of this Journal the author contributed a brief article on wind tunnel drives, referring particularly to some of the installations which had been discovered in Germany after the last war and which The English Electric Company had assisted in dismantling for removal to Britain. One sequel to this operation, which was appropriately known as 'Operation Surgeon', was the official opening by Mr. Aubrey Jones, Minister of Supply, on the 27th of June 1957, of the Royal Aircraft Establishment near Bedford.

THERE ARE AT PRESENT four major wind tunnels completed at the Bedford site of the Royal Aircraft Establishment, and a fifth is in course of construction. Those completed are an 8 ft × 8 ft high-speed wind tunnel, a vertical spinning tunnel, a 3 ft × 3 ft transonic and supersonic tunnel, and a 13 ft × 9 ft subsonic tunnel.

These tunnels involve a total of over 100,000 h.p. of electrical machinery for their main and auxiliary drives, and possibly the most interesting feature to the electrical engineer is the wide variety of variable speed control techniques employed. Grid controlled mercury arc rectifiers feed variable speed D.C. motors, a synchronous induction motor drives a variable pitch propeller, and a Ward-Leonard drive is used in conjunction with a 68,000 h.p. variable frequency synchronous motor fed from a 40 MW gas turbine installation.

The English Electric Company has taken a leading part, not only in supplying new plant, but also in adapting, augmenting and re-erecting the electrical equipment which the Company had previously dismantled in Germany.

3 FT × 3 FT SUPERSONIC WIND TUNNEL

The first tunnel to be completed at Bedford was the 3 ft × 3 ft supersonic wind tunnel and this employed intact the German compressors, gearboxes,

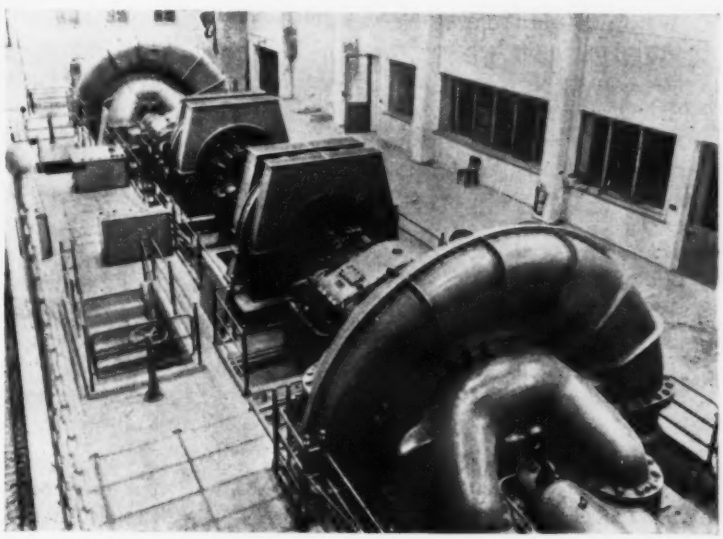

Fig. 1.—German motor-driven compressor set as installed at Volkenrode. It is now in use with the 3 ft × 3 ft supersonic wind tunnel at the Royal Aircraft Establishment, Bedford

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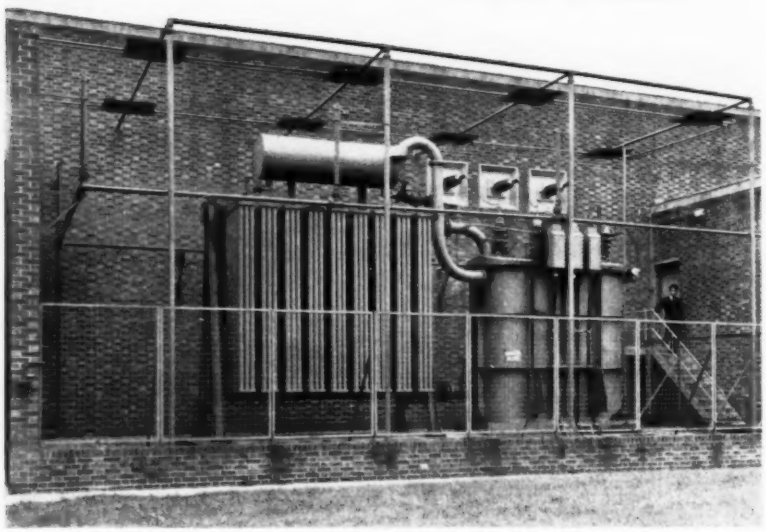

Fig. 2.—'English Electric' 20 MVA 33/50 kV transformer supplying the 3 ft × 3 ft supersonic wind tunnel

D.C. driving motors, and steel tank rectifiers with their transformers, taken from the A.9 wind tunnel installation at Volkenrode near Brunswick in Germany, which is shown in Fig. 1*.

A new tunnel was designed and constructed for use with this compressor equipment, and this can be operated at wind speeds up to a Mach number of 2, but an alternative working section with ventilated walls is also available to enable tests to be carried out in the transonic range.

This tunnel is capable of testing models up to 2 ft wing span and at pressures from 1/20th to 2 atmospheres absolute. The motors driving the German compressors have a rating of 6,000 h.p. each at a maximum speed of 600 r.p.m. They are fed from two multi-anode, grid controlled, water cooled, steel tank mercury arc rectifiers with associated transformers and control gear.

In Germany the rectifier transformers had been supplied at 50 kV and it was necessary therefore to transform the normal 33 kV supply at Bedford to this voltage, for which purpose The English Electric Company supplied a 20 MVA transformer, shown in Fig. 2.

The original German speed-holding equipment for this tunnel had not been satisfactory in service, and The English Electric Company has now developed, manufactured and installed an electronic speed-holding system designed to maintain the compressor speed within $\pm$ 0·1%.

13 FT × 9 FT SUBSONIC WIND TUNNEL

The next tunnel to be completed was the 13 ft × 9 ft subsonic tunnel in which the air is circulated by a 30 ft diameter fan giving a maximum air speed of 300 ft per second. The main purpose of this tunnel is the investigation of low air-speeds such as take-off and landing characteristics of aircraft which are designed for normal operation at transonic and supersonic speeds.

Models up to 10 ft wing span can be tested, and high-frequency motors are mounted in the model to drive miniature propellers or fans to simulate jet flow. The model motors range in power from 2 to 32 h.p. and operate over a frequency range of 0-500 cycles. They are supplied from two German motor-alternator sets obtained from Volkenrode, the speed of which can be varied.

The English Electric Company, in addition to installing and commissioning the German material, supplied a new control desk, together with new instrumentation and additional control and distribution gear.

* *A reproduction of Fig. 5 in the author's article 'Some Notes on Wind Tunnel Drives', E.E. Journal, December 1950, Vol. XII, No. 1, p. 3.*

During test runs it is possible to control from the tunnel control room the frequency supplied to any number up to six of any one type of model motor, and also to indicate in the control room the speeds, power input and temperature of any of these motors.

Auxiliary compressor and evacuator plant is provided for tests involving boundary layer control on models in this tunnel, and this equipment consists of two sets of Lysholm type compressor/exhausters supplied by James Howden & Co. Ltd. and driven by 'English Electric' 2,950 r.p.m. A.C. motors of 450 and 850 h.p. respectively.

The working section of the tunnel is 15 ft in diameter and the air flow, which is of course directed upwards, is under the control of the operator so that the model can remain at the same height and thus be kept under observation during the test.

There is a long shaft between the motor coupling and the propeller, and this shaft and the motor shaft are hollow to accommodate the operating rod from a Lockheed hydraulic mechanism mounted at the top of the motor for controlling the pitch of the fan blades.

The motor can be started and controlled from any one of three observation positions in the

VERTICAL SPINNING TUNNEL

Another interesting tunnel at Bedford, for which The English Electric Company supplied the whole of the electrical equipment, is shown in Fig. 3. This tunnel is designed to test the behaviour of free models in spinning flight, and more particularly to investigate the methods of recovery from a spin.

The tunnel can be pressurised to 4 atmospheres absolute and the maximum air speed is 90 ft per second at full pressure and 140 ft per second at atmospheric pressure.

The air is circulated by a variable-pitch fan driven by a vertically mounted, salient pole, synchronous induction motor with a nominal rating of 1,500 h.p. and a short-time overload capacity of 3,000 h.p. The motor runs at a synchronous speed of 500 r.p.m. and is fed from a 3-phase 50 cycles 11,000 volts supply. The motor together with its exciter set, liquid starter and other control gear, are all mounted on a platform at the top of the vertical tunnel as shown in Fig. 4.

Fig. 3.—Vertical spinning tunnel, showing circular lift shaft

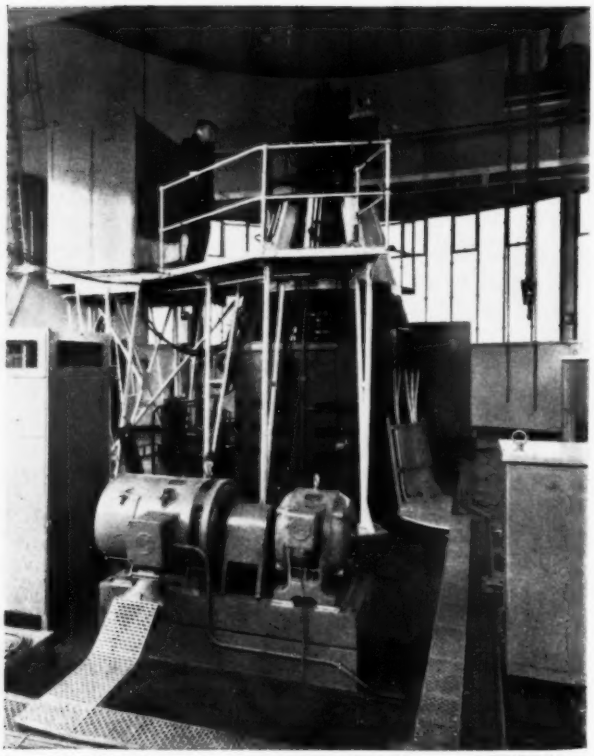

Fig. 4.—'English Electric' 1,500 h.p. vertically mounted synchronous induction motor driving the variable-pitch fan for the vertical spinning tunnel

tunnel, and operation of a single switch at any one point initiates the starting and stopping sequences.

The tunnel structure is 45 ft in diameter and 80 ft high and the fan draws up air through the 15 ft diameter centre working section and returns it to the base of the tunnel through the annular return circuit in the shell of the tower. Models up to 3 ft wing span can be tested in this tunnel.

8 FT × 8 FT HIGH-SPEED WIND TUNNEL

Perhaps the most spectacular tunnel installed at Bedford is the 8 ft × 8 ft high-speed tunnel, part of which is shown in Fig. 5. This tunnel is designed to operate up to a wind speed of M = 2·7 and at

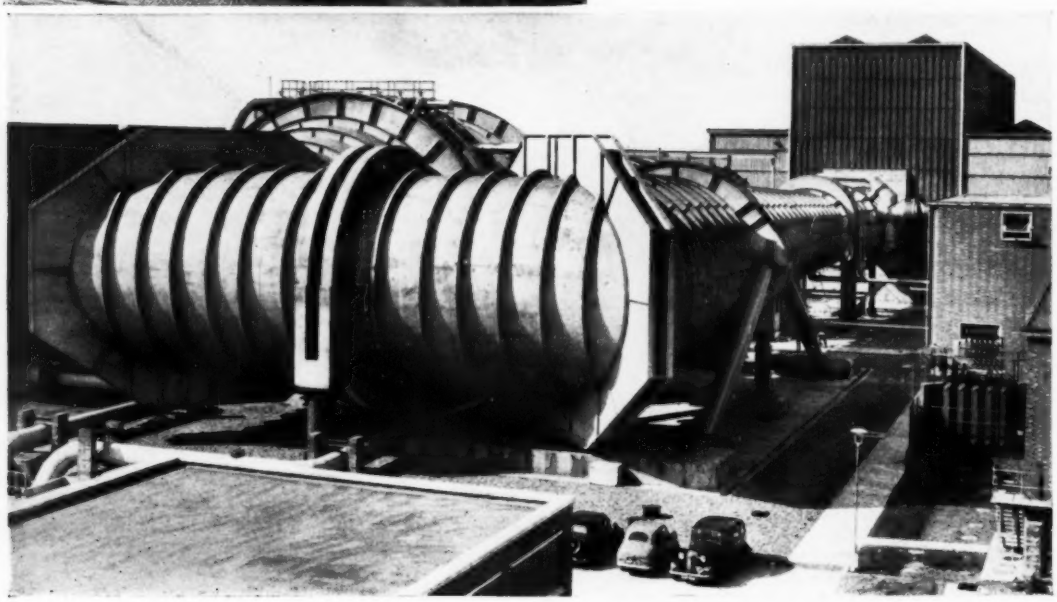

Fig. 5.—Another view of the 8 ft × 8 ft supersonic wind tunnel circuit

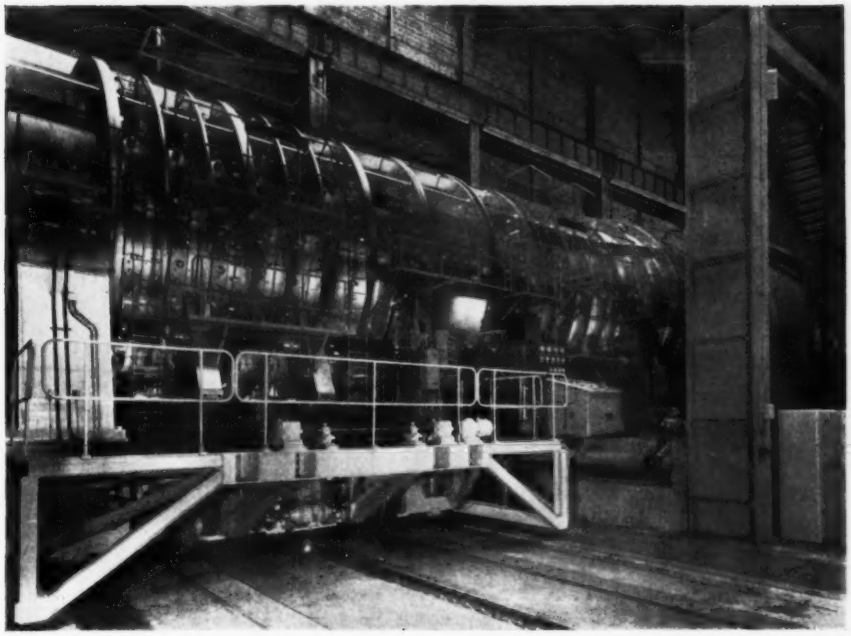

Fig. 6.—'English Electric' compressor for the 8 ft × 8 ft supersonic wind tunnel

pressures from 1/10th of an atmosphere to 4 atmospheres. It has been stated that it is the largest all-welded pressure vessel in Europe as it measures 350 ft between long centres and 60 ft between short centres, the maximum diameter being 47 ft.†

The air is circulated by a ten-stage axial flow compressor mounted in the tunnel circuit and driven by a 68,000 h.p. synchronous motor backed up by two 6,000 h.p. D.C. motors which are provided to give the necessary precision speed control.

The supply for the A.C. motor is obtained from two 20 MW 'English Electric' gas turbine driven alternator sets installed in an adjacent generating station. These provide a variable frequency, variable voltage supply to give the necessary speed control of the main 68,000 h.p. motor.

The English Electric Company was the main contractor for the compressor, driving motors and generator plant, and also for the auxiliary motors, switchgear, lubricating equipment, etc. This work is a good example of the Company's ability to undertake large comprehensive contracts of this nature involving a variety of products and a large measure of general and specialist engineering.

Compressor

The compressor, a view of which is shown in Fig. 6, is an axial flow 10-stage unit with a maximum air flow of 50,000 cubic feet per second (102 tons of air per minute) and it runs at a maximum speed of 750 r.p.m. The English Electric Company was responsible for the mechanical design of this compressor, the aerodynamic design being the responsibility of the Royal Aircraft Establishment.

The compressor is made up of a 4-stage fixed low-pressure section and a 6-stage movable high-pressure section.

The high-pressure section is mounted on a truck so that it can be moved out from the wind tunnel circuit and replaced by a dummy section to cater for certain aerodynamic conditions.

The compressor can absorb an input of 80,000

† *The speed control of this tunnel is described in the Paper 'Speed control of large wind tunnels' given to the Institution of Electrical Engineers in December 1957 by Mr. L. S. Drake of the Ministry of Works, and Messrs. J. A. Fox and G. H. A. Gunnell of The English Electric Company.*

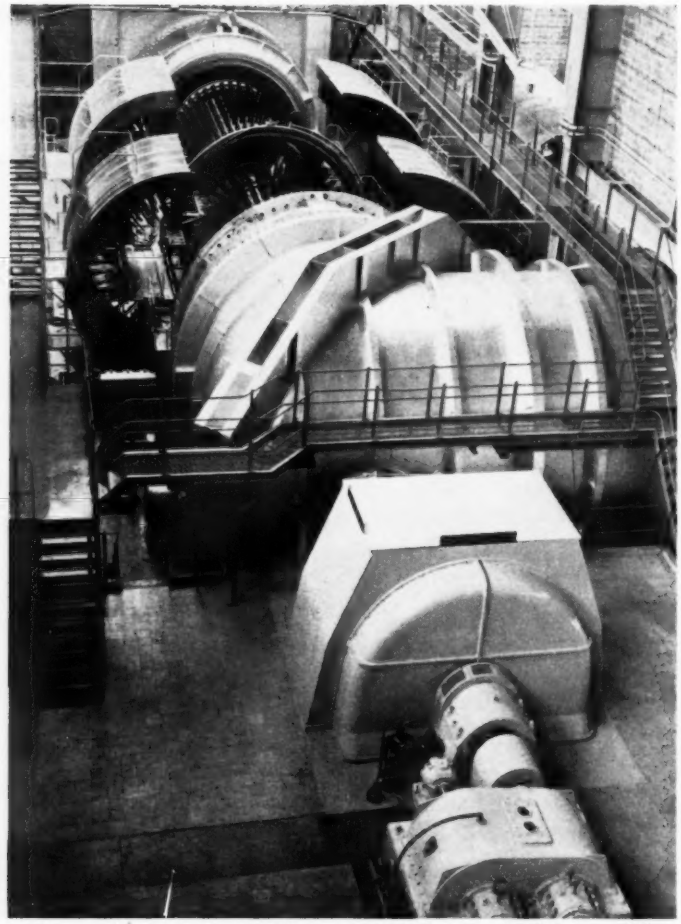

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Fig. 7.—Another view of the compressor for the 8 ft × 8 ft wind tunnel, showing casings withdrawn for inspection and maintenance purposes and, in the foreground, the 68,000 h.p. A.C. motor in the main drive

h.p. but is designed for an ultimate power input of 100,000 h.p.

The following particulars are of interest in visualising the size of this unit :

Overall length of the 10-stage compressor	55 ft
Overall length of compressor with driving machinery	130 ft
Maximum outside diameter of compressor casing	23 ft
Weight of high-pressure section with truck	900 tons
Weight of low-pressure section	600 tons

Each stage of the fan has 53 rotor blades and 52 stator blades, the weight of each blade being approximately 1 cwt. The maximum diameter over blade tips is 17 ft 4 in. The weight of the high-pressure rotor is 124 tons, and that of the low-pressure rotor 87 tons. The total rotating weight including driving machinery is 300 tons.

When it is necessary to remove the high-pressure section of the compressor and insert the dummy section, the pressure behind the hydraulically-operated moulded rubber casing seals at both ends of the stator section is released and the dog-type coupling between the high- and low-pressure shafts withdrawn by means of a hydraulic motor. The truck carrying the high-pressure section is then removed sideways, the operation being carried out by means of a 3 h.p. motor through reduction gearing. The pressure is then reapplied to the seals and the compressor is again ready for operation. The total time for removing or inserting this section is 20 minutes.

The casings of both sections of the compressor are split along the vertical centre line, and after removal of the joint bolts the two halves can be withdrawn on rails to expose the blading and bearings for maintenance purposes. This feature is shown in Fig. 7.

The Compressor Drive

A view of the main drive for the compressor is shown in Fig. 8. The D.C. motors shown are part of the equipment removed from Volkenrode in Germany and run at a maximum speed of 600 r.p.m. Since, however, the best speed for the compressor

was found to be 750 r.p.m., it was decided to run the large A.C. motor at this speed and insert a gear-box between the D.C. and A.C. machines. The gear-box is provided with shaft extensions, one of which provides the drive to the main lubrication oil pumps and the other to a reference tacho-generator required for speed control purposes.

The rating of the A.C. synchronous motor was based on a wind tunnel design requirement of 49,000 h.p. at 540 r.p.m. which requires a frequency of 36 cycles. The corresponding full load rating at 50 cycles is 68,000 h.p.

Barring gear is fitted at the tail end of the drive, as can be seen in Fig. 8. It is designed to rotate the compressor at the very low speed of 1/10th of a revolution per minute and is required to facilitate the operation of coupling the high-pressure and low-pressure stages of the compressor.

The 6,000 h.p. D.C. motors in the drive are supplied from a Ward-Leonard motor-generator set, shown in Fig. 9, consisting of two further similar German D.C. machines obtained from Volkenrode and driven by an 'English Electric' 14,000 h.p. 11,000 volts 600 r.p.m. 3-phase reactor started synchronous motor.

The compressor is always started by means of the D.C. motors, but the power available from them is not sufficient to run the compressor up to its maximum speed unless the tunnel is evacuated.

The compressor can be operated in any one of three ways, namely, by means of :—

(*a*) the two 6,000 h.p. D.C. motors alone, with or without automatic speed control,

(*b*) the two D.C. motors, together with the 68,000 h.p. A.C. motor at constant speed supplied at 50 cycles from the grid system,

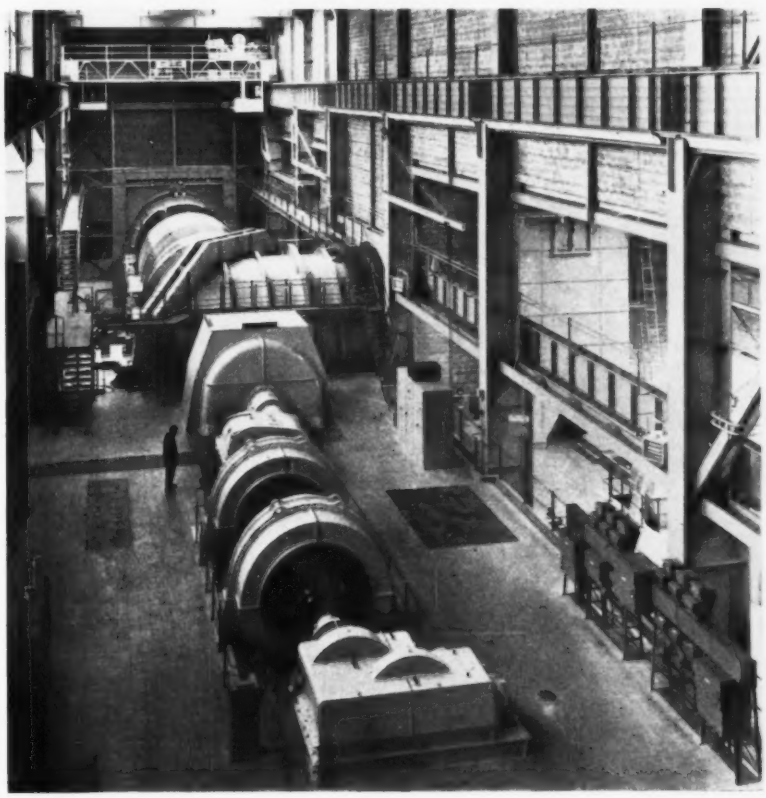


Fig. 8.—The main drive and compressor of the 8 ft × 8 ft wind tunnel

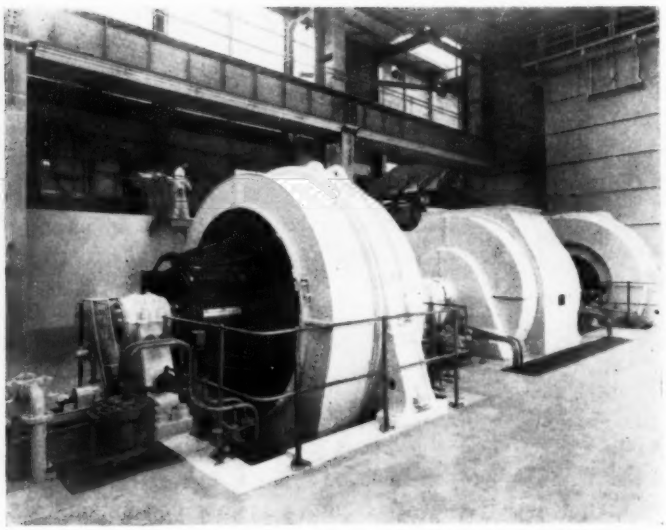


Fig. 9.
Motor-generator set supplying the 6,000 h.p. D.C. motors of the main drive for the 8 ft × 8 ft wind tunnel

(*c*) the two D.C. motors, together with the A.C. motor supplied from the gas turbine driven alternator sets, giving a variable frequency of 10-50 cycles with the resulting speed range on the compressor of 150-750 r.p.m. Automatic or manual speed control is available.

Automatic Speed Control

The fundamental purpose of a wind tunnel is to create a column of air over the surface of a model so that the behaviour of that model can be analysed. It is also fundamental that the conditions in the working section of the tunnel remain constant during the period that readings of the forces exerted on the model are being taken.

In subsonic work the accuracy of the air velocity is primarily a function of the accuracy of the compressor speed, whereas in supersonic work the velocity in the working section for a given compressor speed is dependent on the throat characteristics of the nozzle inserted upstream of the model.

The accuracy of speed setting and speed holding under supersonic conditions depends mainly on

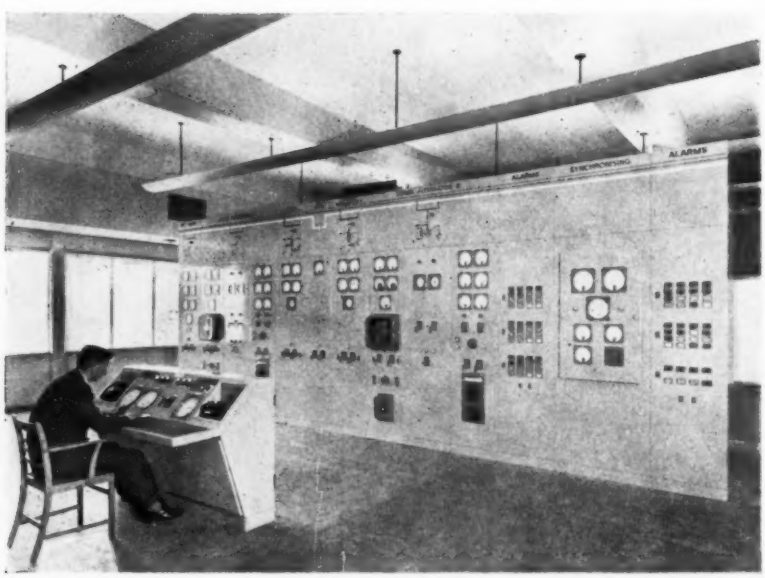


Fig. 10.—'English Electric' control board and desk in the central control room

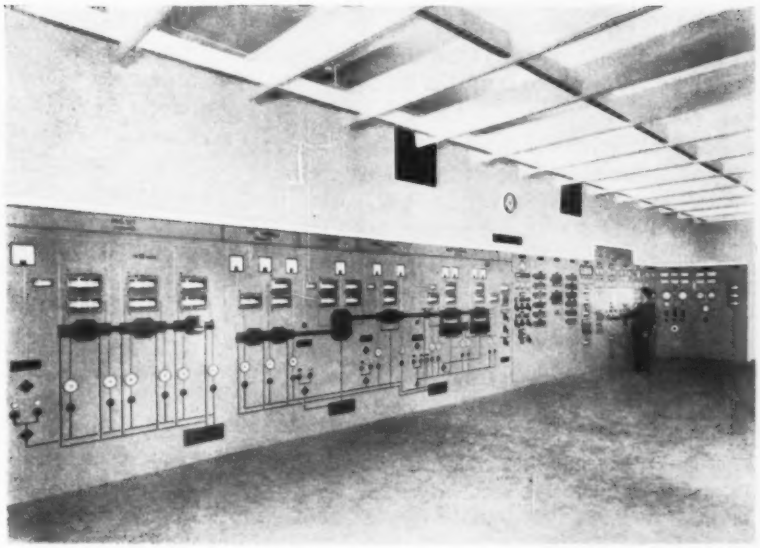


Fig. 11.—*'English Electric' control board in the local control room*

the positioning of the shock waves which are formed at the model at speeds above the speed of sound.

The automatic speed control system has been designed to maintain the compressor speed within ± 0·1% of the set speed over the working range of 150-750 r.p.m. and an accuracy of ± 1·0% over the speed range of 75-150 r.p.m. The speed control system will also permit controlled acceleration of the D.C. machines under current limit control, as well as permitting emergency shutdown under controlled conditions by re-generation in the D.C. loop.

When running under variable frequency conditions, the speed control system operates not only on the excitation of the D.C. generators but also on the fuel valves of the gas turbines driving the alternators, so that the gas turbines can follow up changes in load and speed.

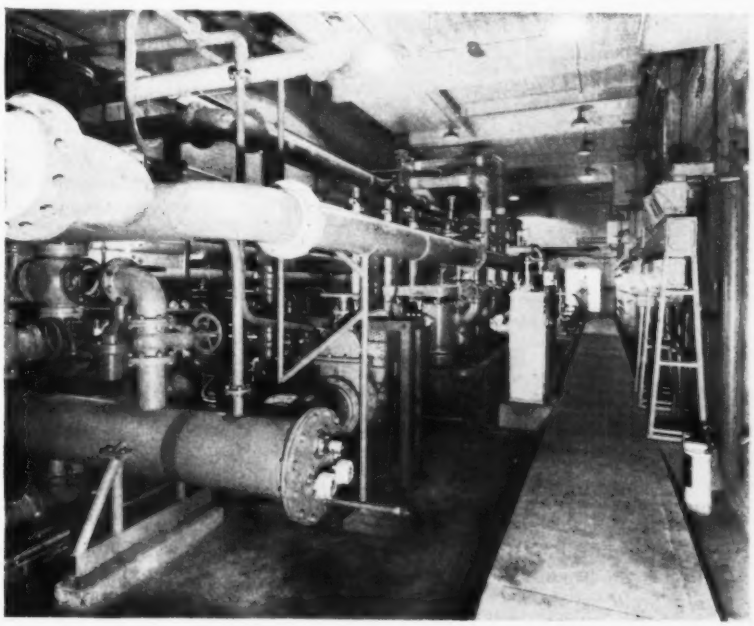


Fig. 12.

Lubrication room for the compressor and main drive motors of the 8 ft × 8 ft wind tunnel

Control Rooms

There are three major control rooms associated with the main drive and its auxiliaries, as follows:—

(*a*) *Observation Room*

The main drive is normally operated from the observation room and the operators have complete control over the drive speed in addition to control and instrumentation of the pressure and temperature in the wind tunnel. Instruments for monitoring the aerodynamic tests are also included in this room.

(*b*) *Central Control Room*

The circuit-breakers in the variable frequency sub-station are controlled from the central control room (Fig. 10). They are of the 'English Electric' 11 kV 1,000 MVA metalclad type with duplicate busbars fed from the grid supply and gas turbine generating sets respectively. Synchronising of the main A.C. motor with the variable frequency alternators or the grid supply is carried out from this room, and also supervision of instrumentation and alarms on associated equipment.

(*c*) *Local Control Room*

Operation of the main Ward-Leonard motor-generator set and all auxiliaries associated with the main drive, including excitation control of the 68,000 h.p. A.C. motor, lubrication system of the main drive, tunnel sealing, and starting up of the drive, is carried out from the local control room (Fig. 11) before handing over control to the observation room.

Lubrication System for Compressor and its Drive

The lubrication equipment (Fig. 12) was sub-contracted to Denco Engineering Services Ltd at Hereford and it is housed in lubrication rooms at basement level. It is divided into four groups supplying respectively the bearings of the main compressor, the main drive motors, the David Brown gear-box and Ward-Leonard motor-generator set. An Electroflo mimic diagram panel housed in the local control room (Fig. 11) shows the system in diagrammatic form, with flow meters, pressure gauges and thermometers in their appropriate positions.

In the first three groups the flood pumps are mechanically driven from the main drive gear-box, and in the last group, from the motor-generator set shaft. Each group has an electrically driven standby unit which automatically cuts in if the flow from the mechanical drive pump is below a predetermined volume. When the flow from the mechanical pump is established, the electrically driven units cut out automatically. Electrically driven jacking pumps are also provided on all the main drive bearings, and the oil is filtered and cooled before being delivered to the bearings and again before returning to the pumps. In the high-pressure section of the compressor, the oil is supplied and returned via special valves in the clamping boxes of the removal truck.

Gas Turbine Generating Sets

The two 'English Electric' gas turbine generating sets are of the compound open cycle type, each driving a 20 MW alternator. These sets are capable of operating over a speed range of 5 : 1, giving a variable frequency range of 10 to 50 cycles per second for supplying the main A.C. motor driving the wind tunnel air compressor.

Each gas turbine engine employs intercooling without reheat or heat exchange, and uses two stages of compression and two of expansion, with a free power generating turbine operating in parallel with the turbine driving the low-pressure compressor.

Air is initially compressed in the low-pressure compressor, passes through the intercooler and is further compressed in two parallel high-pressure compressors. After passing through the combustion chambers, which form an integral part of the high-pressure sets, the heated combustion gas expands first in the high-pressure turbines driving the high-pressure compressors. Finally, the gas expands in the two low-pressure turbines, one of which drives the low-pressure compressor while the other drives the alternator.

Air enters the low-pressure compressor through air filters mounted at the entry to ducts behind the louvred outside wall of the generator house. The compressor is of the axial flow type employing thirteen stages.

The intercooler is of the single pass cross-flow type employing water as the cooling medium, and from this the air is taken through a duct, bifurcated at its end to feed in parallel the two high-pressure compressors. These are of an axial-centrifugal design employing six axial flow stages with vortex type blading and a single centrifugal stage formed on the outlet end of the axial rotor drum.

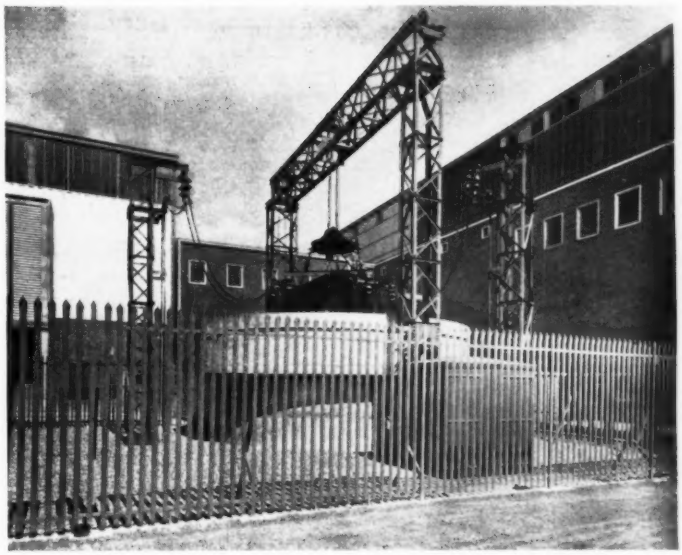


Fig. 13.—'*English Electric*' *adjustable load tank for testing the* 20 *MW gas turbines*

The high-pressure turbines are both of the axial flow type with two stages of ' free-vortex ' blades. The low-pressure turbines employ 6 blading stages.

Lubricating and fuel oil pumps are driven from the high-pressure compressor shafts through gear-boxes. The lubricating oil pumps are also used as hydraulic motors for starting and barring-over the high-pressure elements of the units, oil for this purpose being obtained from a battery of 50 h.p. motor-driven pumps which can also assume the duty of lubricating oil pumps.

The tunnel design point of 49,000 h.p. at 540 r.p.m. corresponds to an input to the large A.C. motor of 37·2 MW at 36 cycles, and the two-pole variable frequency alternators are rated at 19 MW 7·92 kV at 36 cycles with voltage and output proportional to frequency over a range of 10-50 cycles. The characteristic of the gas turbine however is such that no more than 20 MW can be given at 50 cycles.

When not performing their primary duty of supplying power at variable frequency for the drive of the 8 ft × 8 ft wind tunnel, these turbo-alternators are of course available for supplying other site loads.

Each gas turbine has a separate control desk in the generating station on which are mounted all electrical and mechanical controls, instrumentation and alarms. The speed of the gas turbines can be controlled manually from these desks as well as from the observation room or central control room. Automatic control of the turbine fuel valves is also provided as part of the main drive speed control scheme.

A load-tank equipment located outside the generating station was also supplied by The English Electric Company for testing the gas turbines on site, and this is shown in Fig. 13.

Standby Diesel Station

Certain auxiliary motors in connection with the

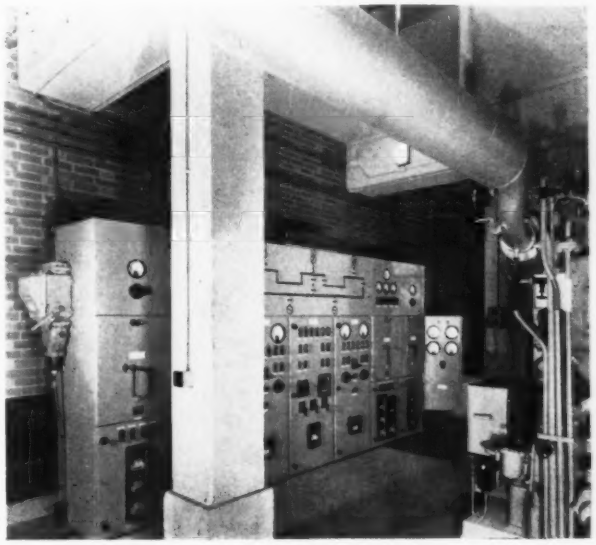


Fig. 14.—'*English Electric*' 7*-panel switchboard with air-break circuit-breakers for the standby diesel station*

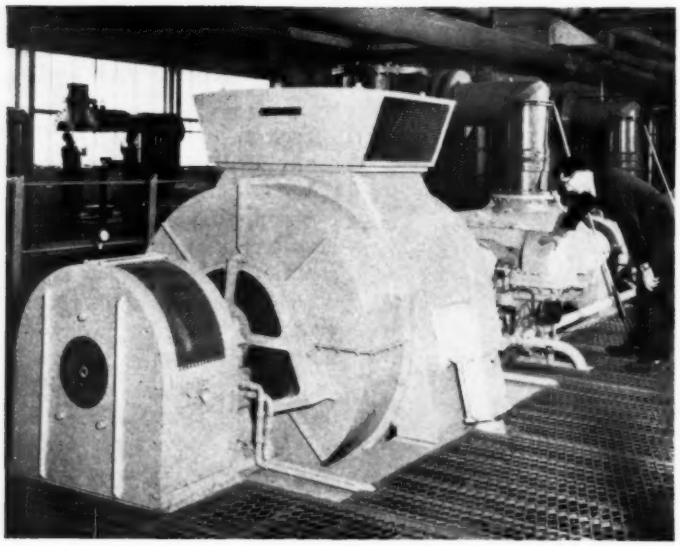


Fig. 15.—'English Electric' 2,000 h.p. 2,950 r.p.m. slipring motor driving Lysholm evacuators for the 8 ft × 8 ft wind tunnel

gas turbines must be kept running even on failure of the local supply, and therefore two diesel-alternator sets were installed to supply power at 415 volts 3-phase 50 cycles to be available on failure of the mains supply. These two alternators and their feeder circuits are controlled by 'English Electric' switchgear (Fig. 14) comprising 15 MVA air-break circuit-breakers and synchronising equipment and two distribution boards with 25 MVA air-break circuit-breakers and H.R.C. fusegear.

Auxiliary Plant

Evacuation of the tunnel to 1/10th of an atmosphere is effected by two sets of Lysholm evacuators supplied by James Howden & Co. Ltd., one of the sets being shown in Fig. 15. The two low-pressure evacuators in each set are driven by an 'English Electric' 2,000 h.p. 2,950 r.p.m. slipring motor, and the high-pressure machines are driven by similar but smaller motors rated at 635 h.p.

The pressure in the tunnel is raised above atmosphere by means of two 3-stage single flow charging compressors supplied by Daniel Adamson and driven through David Brown speed-increasing gear-boxes by 1,730 h.p. 'English Electric' 1,480 r.p.m. slipring motors as shown in Fig. 16. These two charging compressors can be used either in series or parallel, depending on the pressure required in the tunnel. James Howden & Co. Ltd. also supplied two trimming compressors to maintain constant the established tunnel pressure, and these are driven by 380 h.p. 'English Electric' 1,450 r.p.m. motors.

These evacuators and compressors in the auxiliary plant room all operate from a 3,300 volts 3-phase supply, and the switchgear for the motors and

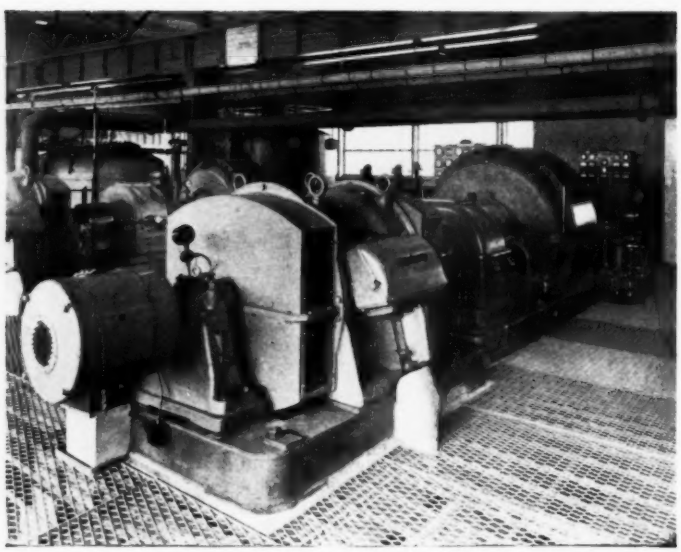


Fig. 16.—'English Electric' 1,730 h.p. 1,480 r.p.m. slipring motors driving charging compressors for the 8 ft × 8 ft wind tunnel

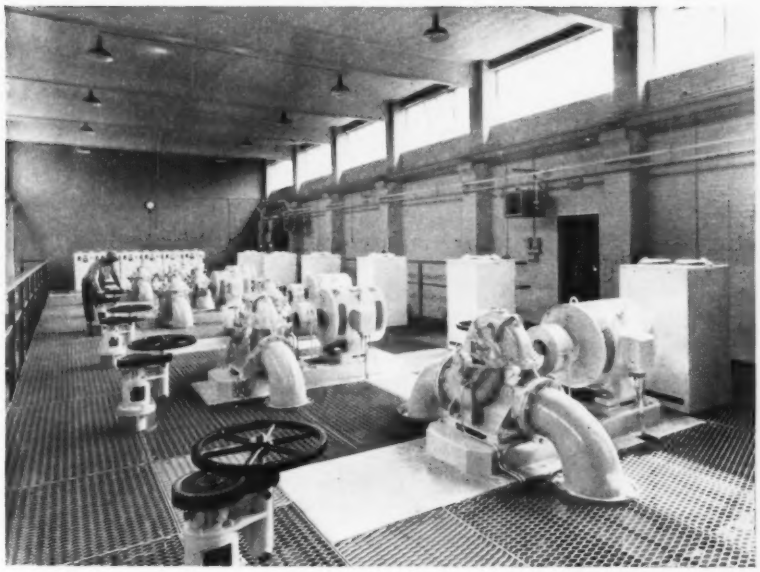


Fig. 17.—*Six of the twelve* '*English Electric*' 170 *h.p. squirrel-cage motors driving the water pumps for the cooling system of the* 8 *ft* × 8 *ft wind tunnel*

the liquid controllers for their rotor circuits were all supplied by The English Electric Company.

Tunnel Cooler

In a closed circuit wind tunnel it is necessary to remove heat from the airstream at a rate equal to that of the supply of energy from the fan or compressor, if the temperature of the air is not to rise continuously.

With 80,000 h.p. input, clearly a very large

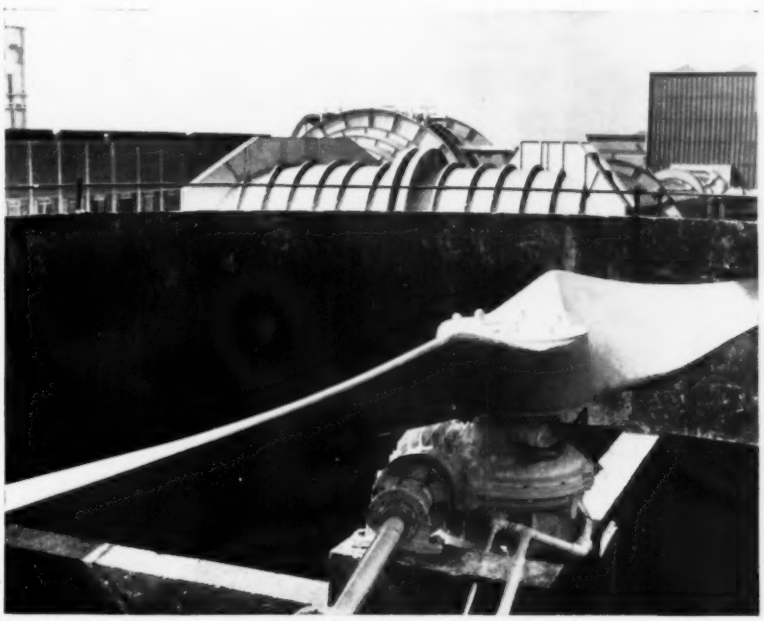


Fig. 18.—*One of the eleven fans in the cooling towers*

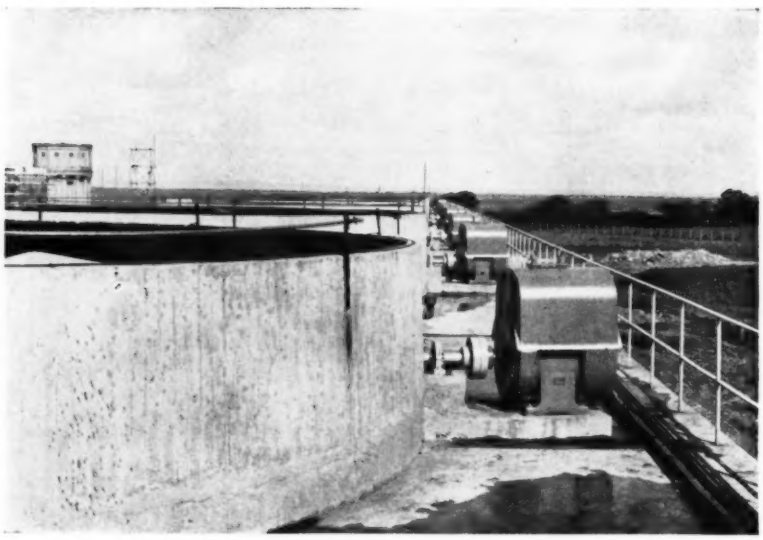


Fig. 19.—*'English Electric' 60 h.p. closed-air-circuit squirrel-cage motors driving the fans as shown in Fig.* 18

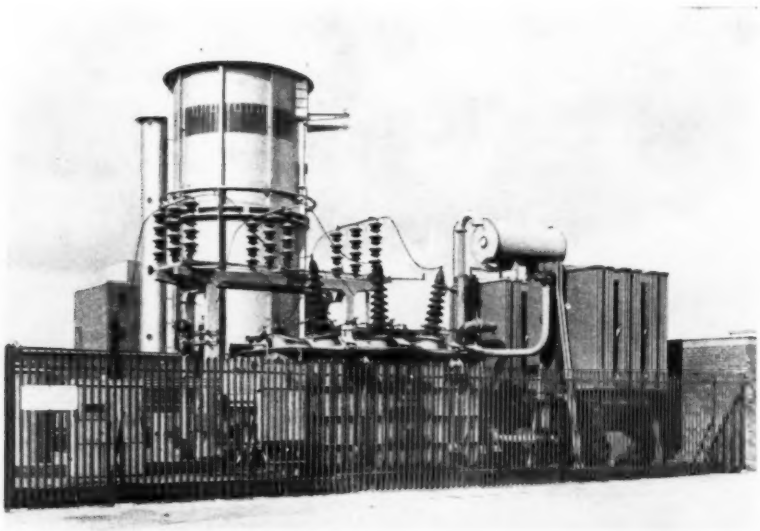


Fig. 20.—*'English Electric' 75 MVA* 132/33 *kV transformer in the sub-station feeding the Royal Aircraft Establishment, Bedford. In the background is the vertical spinning tunnel*

cooler is required, and 12 pumps each with a 170 h.p. motor and 11 cooling tower fans each with a 60 h.p. motor are used in the cooling system for this tunnel. Fig. 17 shows the water pumps and Figs. 18 and 19 one of the cooling tower fans and the motors driving them.

Power Supply and Distribution

In addition to the work carried out on the four wind tunnels described, The English Electric Company supplied to the Central Electricity Authority the main 75 MVA 132/33 kV transformer for the sub-station feeding the site, and this is shown in Fig. 20.

The Company also supplied the 33 kV distribution switchgear to the order of the Ministry of Works, this comprising a 9-panel 750 MVA duplicate busbar metalclad switchboard with associated relay panels.

Electrical Drives in the Rubber Industry

FOR BANBURY MIXERS, RUBBER MILLS AND CALENDERS

By D. B. PERRY, Electrical Plant Section, and R. J. LANMAN, Machine Control Engineering Department.

IN RECENT YEARS, several large tyre and rubber manufacturers have been engaged in modernisation and expansion schemes for the production of automobile, aircraft and cycle tyres, conveyor belting and domestic products. This opportunity has been taken to review and streamline production techniques, improve working conditions and standards of safety, and plan for future market requirements.

This article outlines the activities of The English Electric Company in providing the electrical machines and control gear associated with a new factory and other plant extensions recently undertaken by The Goodyear Tyre and Rubber Company (Great Britain) Limited. The Banbury mixers, rubber mills and calenders, as installed, are discussed together with factors which influence the selection of electrical equipment.

Banbury Mixers

The Banbury mixer (Fig. 1) is the basic unit for the mixing and compounding of rubber stock, the main elements of which are natural rubber, carbon black and sulphur. Mixing is carried out by means of two rotors in close proximity and on which are formed cams arranged in an interrupted spiral, the arrangement being illustrated in Fig. 2.

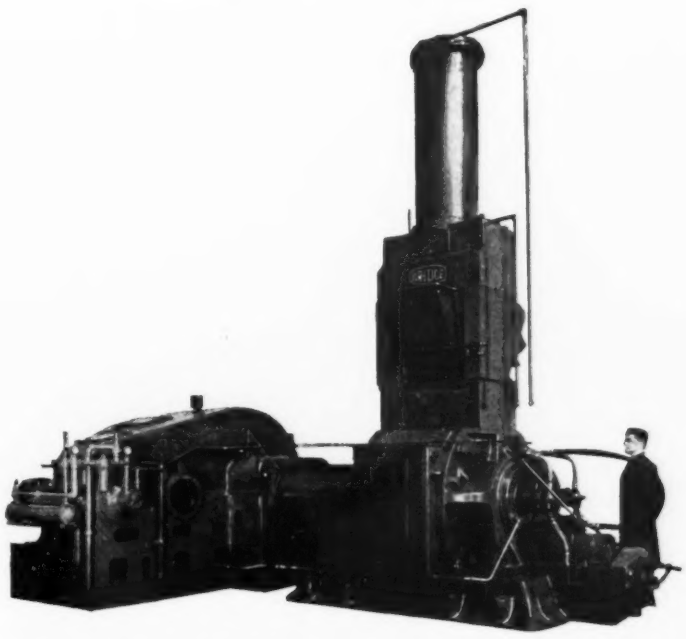


Fig. 1.—*A size* 11 *Bridge-Banbury mixer with Uni-Drive gearbox*

A slight speed difference is provided between the two rotors and constant intermixing is thus assured, but the length of the mixing cycle varies appreciably with the proportions of constituents in the batch.

Driving Motors

The shape of the mixing rotors and the cycle time have an important influence on motor design. A typical wattmeter chart is shown in Fig. 3. Normally the mixer is started unloaded, and therefore the starting torque is only that required for ' breakaway ' and is relatively low. It is necessary however to provide for starting under load, after say a supply failure or a 'trip' due to heavy overload. The load in such cases can be relieved to some extent by reducing the ram

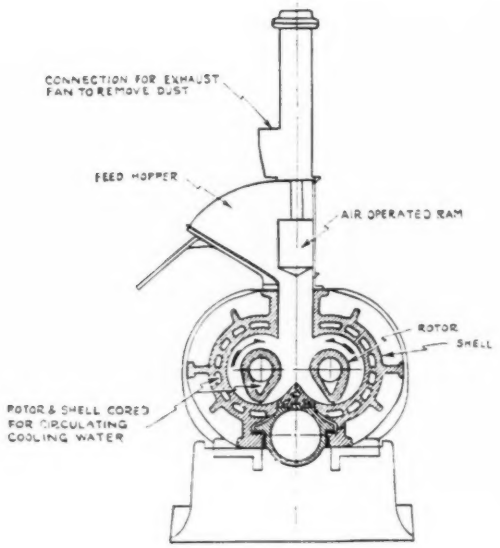


Fig. 2.—Schematic section through Banbury mixer

pressure and by short reversal of rotation.

A general torque specification based on users' experience is given below, although in every case the motor rating is agreed with the user and machinery builder.

TYPE OF MOTOR	TORQUE—% FULL LOAD		
	Starting	Pull in	Pull out
Synchronous induction	125-150	120-130	250
Slipring or squirrel-cage	125-150	—	250

Synchronous motors have been used but in the authors' opinion the application is not really ideal as an inherent constant-speed characteristic is not essential to the process. The power-factor correction properties are also of doubtful value on a peaky batch-load application.

The slipring motor makes available high starting and accelerating torques in conjunction with appropriate values of external rotor resistance, and this is ideal for Banbury mixer duty. Starting torque and current are nearly proportional up to the maximum starting torque of the motor, hence a starting torque of 200% full load results in a line current of not more than say 250% rated current.

Rubber grade carbon known as 'carbon black' is used in the processing of most rubber products and is characterised by the extreme fineness of its particles. For this reason and by virtue of its penetrating properties, low resistivity and increase of conductivity with temperature, it definitely shortens the life of motor insulation when present in sufficient quantity, due to the setting up of dielectric stresses. It can also cause flashover on sliprings and commutators. Conditions progressively improve on moving away from the Banbury location and the problem is not so acute for other drives, such as mills and calenders.

Various types of motor enclosure have been put into service over the years to meet such atmospheric conditions, e.g. drip proof, pipe ventilated, and

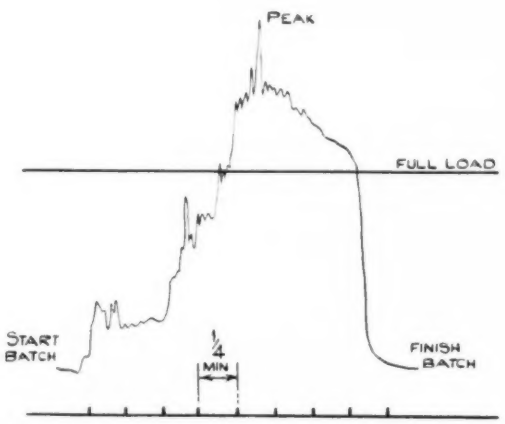


Fig. 3.—Wattmeter recording for a typical Banbury mixer batch cycle

closed-air-circuit air cooled (C.A.C.A.), but for the latest installations of the Goodyear Company, totally enclosed motors with air/water heat exchangers (C.A.C.W.) are used and they possess several desirable features. Fig. 4 shows such a machine. The heat transfer is air to water, hence the problem associated with C.A.C.A. construction of keeping external air circuits unobstructed is avoided. Additionally, the advantage of having an

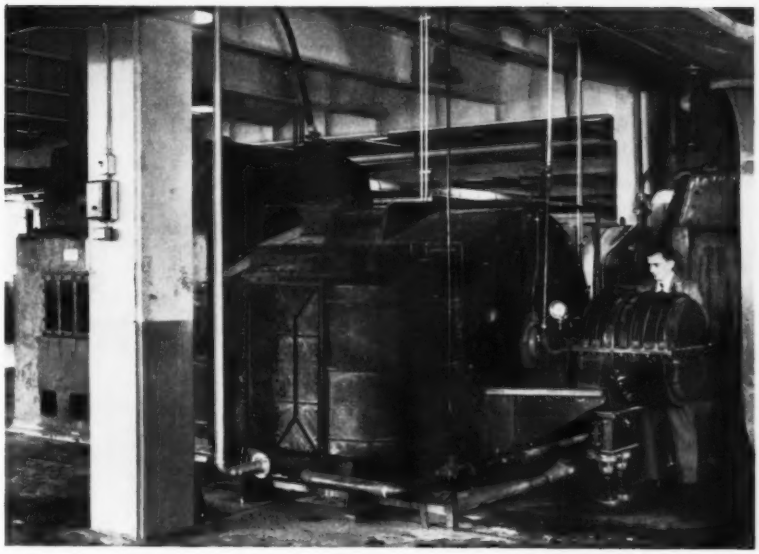


Fig. 4.—A 1,500 h.p. 6,600 volts 743 r.p.m. 'English Electric' closed-air-circuit slipring induction motor with special anti-carbon-black features, driving a Bridge No. 11 Banbury mixer with Uni-Drive

internal closed air circuit for the recirculated air is retained.

Although the motor is totally enclosed, 'breathing' takes place when cooling down or heating up and this is significant for this type of enclosure in the presence of carbon black. By creating facilities for the motor and slipring enclosure to 'breathe' through filtered breathers, and by fitting space heaters in the carcase to keep the temperature difference small between idling and full power, trouble due to the infiltration of carbon black is largely overcome. The breathers incorporate replaceable dry-type elements. Attention to endshield joints, the fitting of close-tolerance shaft seals, the treatment of windings, the provision of special slipring enclosures and special bearing seals, all contribute to the success of the overall design.

Control Gear

Control gear used with Banbury mixers must provide for occasional reversing and inching in addition to the usual control functions. In certain other rubber machinery drives it is essential to provide means of rapidly stopping the machine, but this does not apply to Banbury mixers as the safety of personnel is not involved because the working parts are totally enclosed.

The inertia contribution of the driven components of a mixer is small, and the nature of the process ensures that the machine comes to rest fairly quickly on disconnection of the motor supply.

The siting of controls is important and it is usual for the main panels to be located in a separate room where the atmosphere is free from carbon black. Facility for local control at the operator's platform is of course necessary.

Rubber Mills

A simple open roll mill comprises two rolls with a speed differential between the rolls of anything between 10 and 25 per cent to provide a friction ratio. The front roll is the slower of the two and can have a surface speed of between 60 and 160 f.p.m. depending on process requirements. A motor can drive a single mill or a number of mills mechanically coupled. A diagramatic layout is shown in Fig. 5.

Mills are used for various duties and the roll surface may be smooth, spirally grooved or corrugated, according to the process. The power requirements vary on this account and according to the process.

Uses of mills are :—

Sheeting ('ironing out' stock from Banbury mixer).

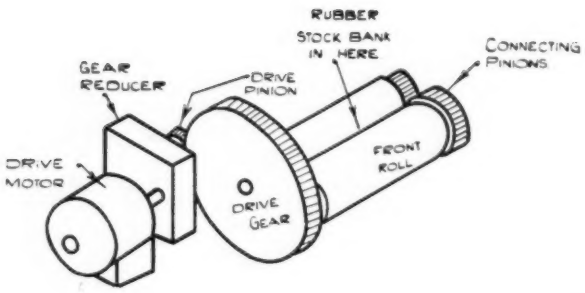


Fig. 5.—Arrangement of single roll mill

Breaking (reducing crude stock to required plasticity).
Mixing rubber stock with other ingredients.
Warming cold stock for feeding to calenders.
Cracking (shearing and tearing reclaimed material).
Washing (cleaning crude rubber stock).

Rating of Motors

On rubber mills the momentary peak torques can be high, and generally accepted figures are as follows :—

Individual drive :

Synchronous—150% starting, 100% pull in, 250% pull out.
Slipring —150% starting, 250% pull out.

Group drive :

Synchronous—125% starting, 110% pull in, 225% pull out.
Slipring —125% starting, 225% pull out.

The method used by the mill makers and users for declaring the rating of motors for mill duty is not standardised, largely because the characteristics of mills are difficult to define. Clearly, however, milling of cold stock and restarting with stock in the rolls can result in loads in excess of those required for normal running. In the case of the motors for the Goodyear installation, a load plus overload rating was specified in accordance with B.S.168 together with a pull-out torque of 250% full load. It is also quite usual for say 25% overload for two hours and 50% for half an hour to be asked for. Where mills are known to be processing one particular type of stock, there has been in the

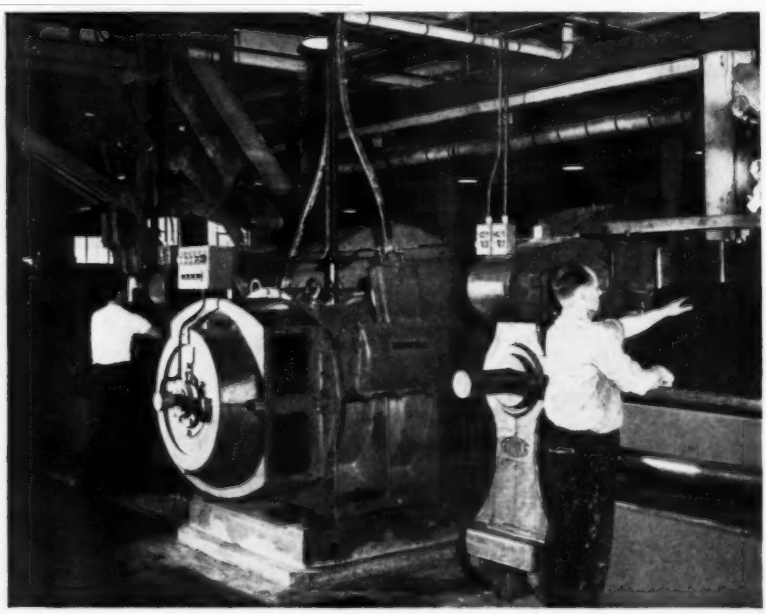


Fig. 6.—A 400 h.p. 6,600 volts 743 r.p.m. 'English Electric' protected enclosure slipring induction motor driving two rubber mills through right-angle bevel gears

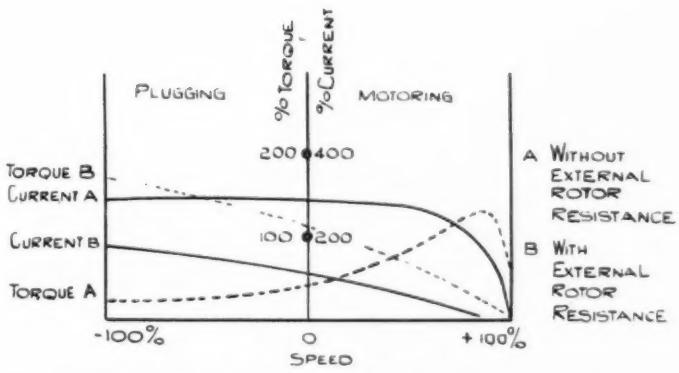


Fig. 7.—Comparison of the torque and current characteristics for a slipring induction motor with and without external rotor resistance

authors' opinion a good case for rating the motors to suit the anticipated R.M.S. and peak loads. Now that B.S.2613 has been established, the covering of excess load conditions by specifying an overload capacity can quite often result in the selection of a motor that is too large for the drive and high in cost.

Safety Measures—Stopping

The size and design of the motor is also important from other aspects. Rotor inertia and pull-out torque are of particular significance when considering the stopping problem.

Open-roll mills present safety hazards due to the fact that the operators must work in close proximity to the rolls. The shorter the stopping time, the larger becomes the safe working area on the roll surface prior to the nip of the rolls. The National Joint Industrial Council Report issued in 1952 calls attention to the fundamental principles which have been proved to be essential for safe working, and it is useful to quote the following extract from this Report.

> " In general, a braking distance of more than a quarter revolution will affect adversely the proper use of the mill. On actual cases, the braking distance on large rolls can be made as short as one ninth of a revolution. It is to be noted particularly that the braking distance should not be represented as a function of the roll surface speed, otherwise a condition may be obtained where by reason of high surface speeds the braking distance may exceed one revolution, a condition incompatible with safe working, as the Report shows."

The roll travel with emergency stopping by 'plugging' on the Goodyear mills is about $\frac{1}{8}$th of a revolution measured on the front roll. Two main factors govern the roll travel during an emergency stop; (1) the time lag between trip-bar operation and the establishment of braking effort, and (2) the rate of retardation after braking effort is applied. Both these points have great influence on the design of control systems and machines.

It is necessary to have a motor with low rotor inertia and a rotor design which permits a uniformly high reverse torque for good braking

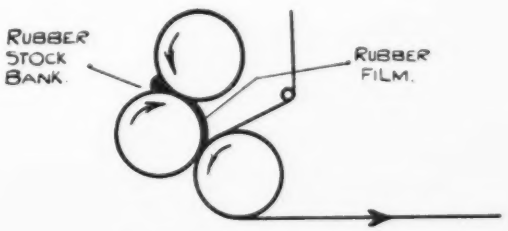


Fig. 8.—Calendering process

coupled with a pull-out torque not in excess of that specified for normal running.

Totally enclosed machines, with their greater dimensions, are only to be recommended in very badly contaminated areas, as for reasons already outlined it is desirable to keep the motor size and hence rotor inertia as small as possible.

Fig. 6 shows one of several protected type slipring motors driving twin rubber mills. The machines have internal sliprings to permit the mounting of the 'zero speed' plugging switch which is visible in the picture.

The inertia of the mill rolls and gears even when running light is small compared to that of the

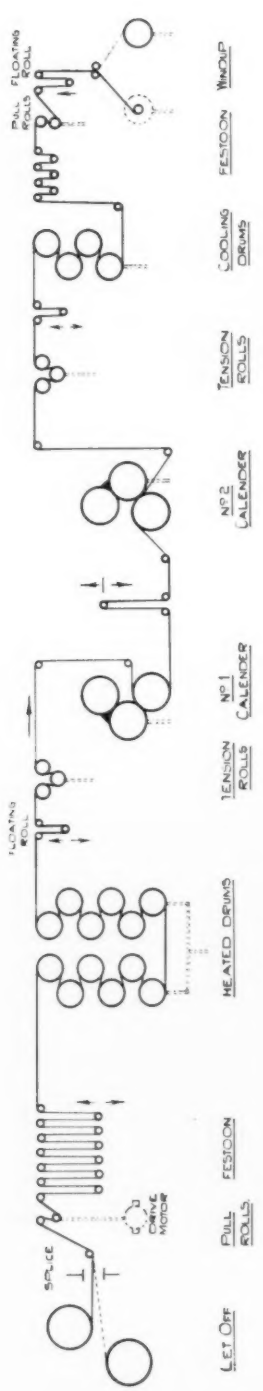


Fig. 9.—Continuous double rubber coating calender train for tyre fabric

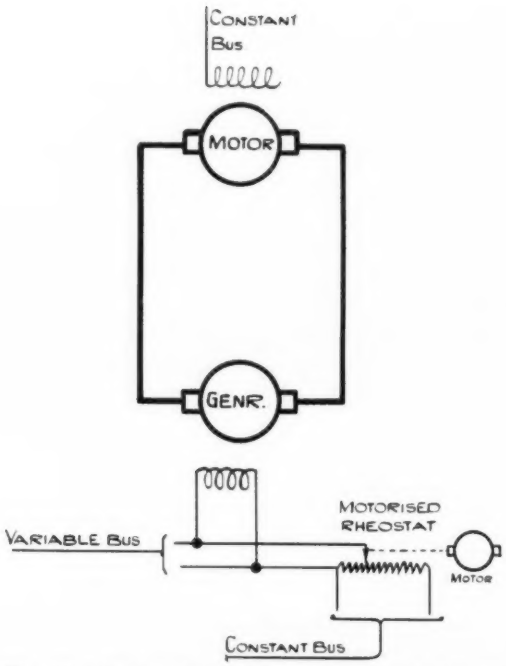


Fig. 10.—Basic scheme showing motorised rheostat supplying the variable voltage busbar to set the operating speed

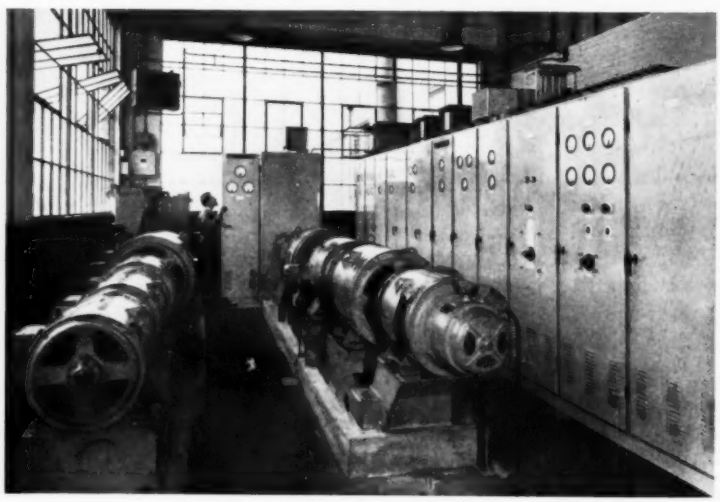


Fig. 11.—'English Electric' auxiliary and exciter sets for calender train, with D.C. main and auxiliary control cubicles

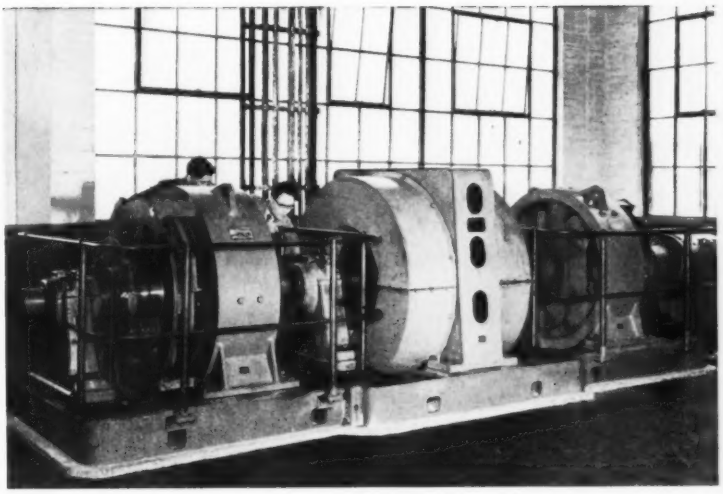


Fig. 12.—*'English Electric' motor-generator set for main calender motors, comprising two D.C. generators driven by a* 700 *h.p.* 1,000 *r.p.m.* 6,600 *volt synchronous motor*

motor rotor, approximately in the ratio of 1 : 4 or even higher. The method of braking is selected with this in mind.

Synchronous induction motors are not widely used, as due to the mill load characteristic their choice only shows to advantage where it is possible to drive a group of mills. Dynamic braking is then employed for emergency stopping.

'Plug' braking is commonly used for the emergency stopping of induction motors, and for machines of the slipring type the reverse torque can be adjusted to suit requirements by the insertion of external resistance in the rotor circuit. Typical torque/speed/current curves are shown in Fig. 7.

Calender Drives

In common with mills and mixers, the calender is a basic processing unit and is used for coating

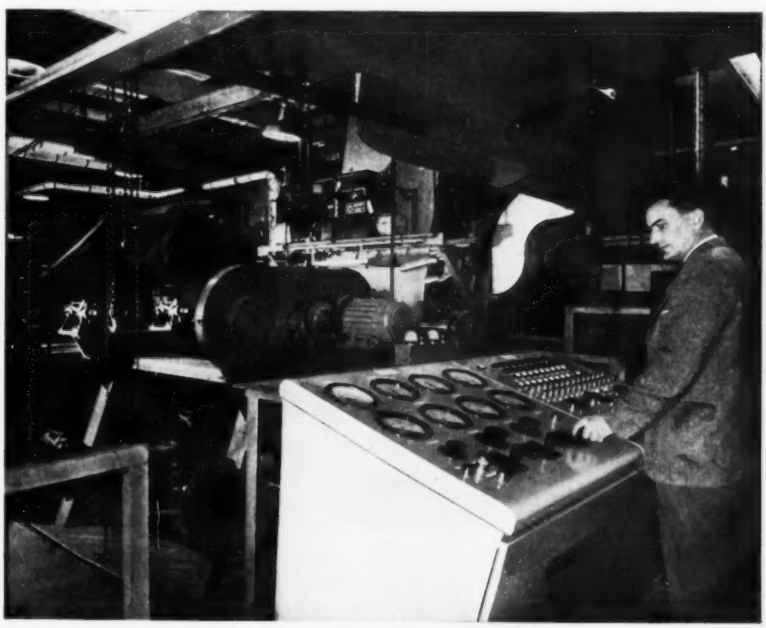
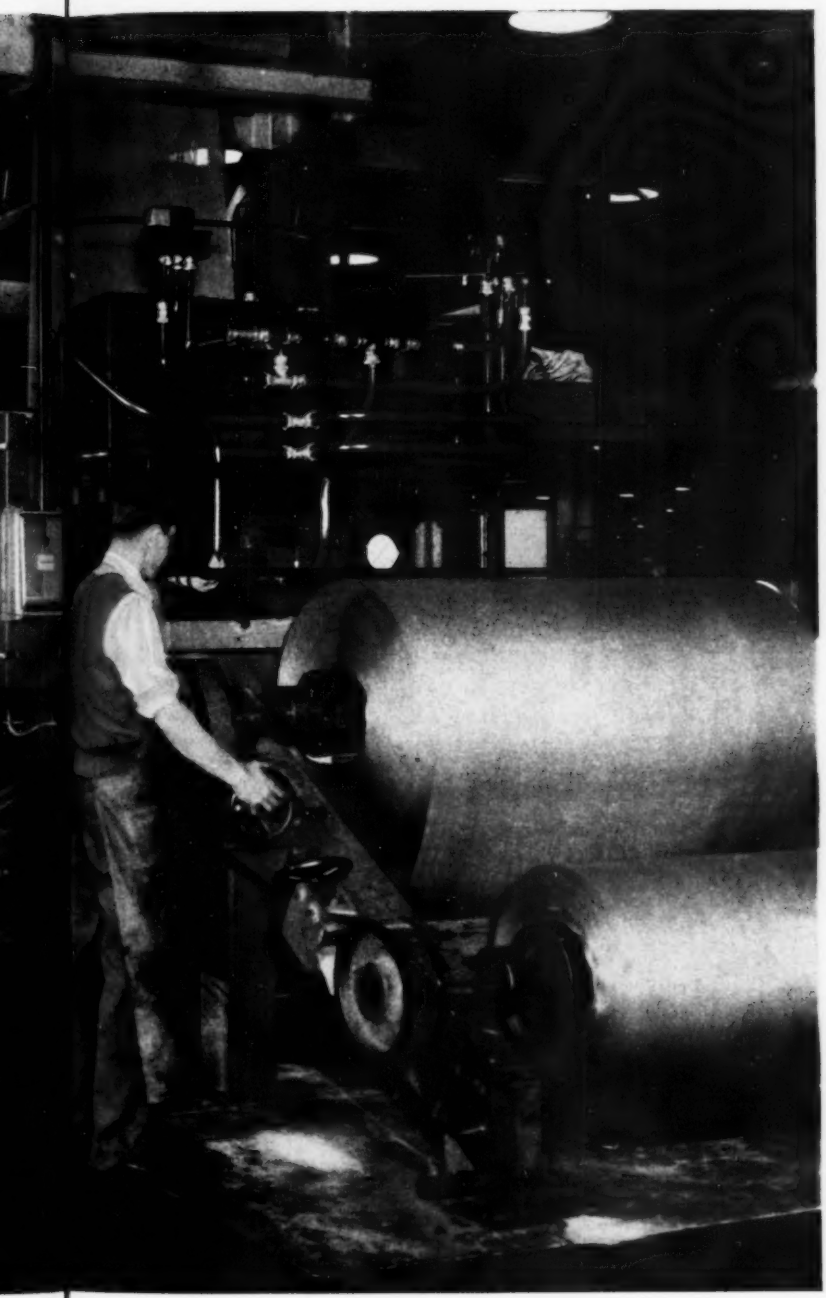


Fig. 13.—*Control desk for double-coat tandem calender train drive*

Automatic tandem calender train in the works of the Goodyear Tyre and Rubber Company (Great Britain) Limited, viewed from the let-off end. The let-off pull rolls motor can be seen in the top left of the picture, and the drying-



drums motor in the middle left. The electrical drives and control equipment for this calender train, and also for Banbury mixers and rubber mills in these works, were designed and provided by The English Electric Company

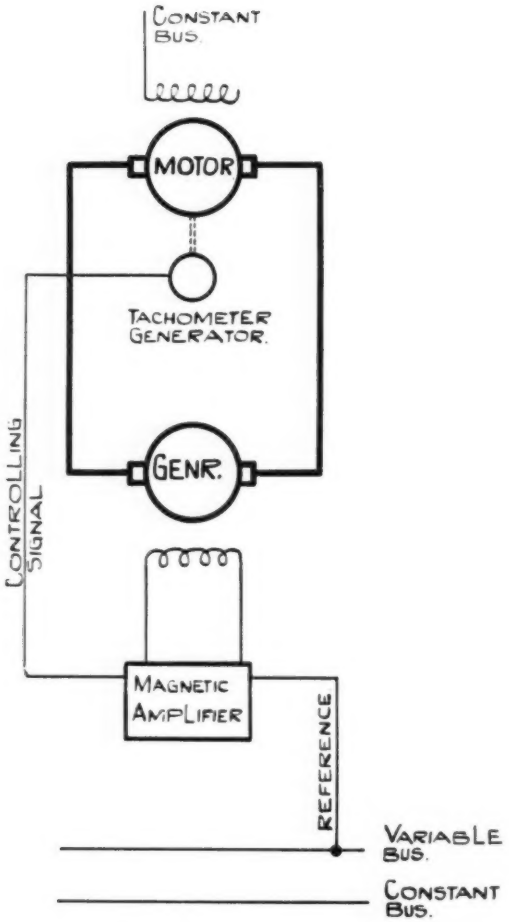


Fig. 14.—Speed control of calender by magnetic amplifier control of generator excitation

tyre fabric with rubber, the rubber providing a bond between the fabric layers constituting a tyre.

A rubber calender consists of precision-ground steam-heated steel rolls through which the fabric passes to receive the coating of rubber. In the three-roll calender, shown diagrammatically in Fig. 8, a film of rubber from the stock bank passes around the centre roll to be pressed into one side of the stranded cord fabric between the centre and bottom rolls. For normal coating the rolls are geared to run at similar speeds, but sometimes the top and centre rolls are run faster than the bottom roll and the rubber is thus 'frictioned' into the fabric for better adhesion.

The simplest form of calender unit comprises the calender itself, a let-off for the uncoated fabric and a wind-up for the single coated fabric, the process necessitating the fabric being passed through the calender a second time to obtain a coating of rubber on each side. Due to the demand for higher standards of the finished tyre fabric and increased production requirements, the high-speed continuous multi-processing train has evolved.

Calender Train

The layout of the calender train in the Goodyear works is illustrated in Fig. 9 showing the twin calenders, the fabric flow and all the auxiliary drives forming the complete working unit. All the motors are D.C. and are supplied by variable voltage D.C. generators under Ward-Leonard control to obtain variation in fabric operating speed and also the required smooth co-ordinated acceleration and deceleration of the whole train. The basic scheme for an individual drive is shown in Fig. 10 where the main fields of the generators are supplied by the variable voltage exciter whose field is controlled by the motorised rheostat to provide the variation in train operating speed.

The calenders are the most important units in the train, and as their motor horse-powers are much greater than those of the auxiliary drives their speeds are not normally influenced by small variations in speed of adjacent auxiliaries, so that speed control can be centred on the calender drives.

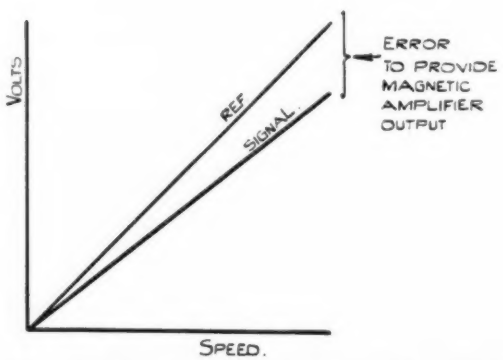


Fig. 15.—Comparison between calender speed reference and controlling signal

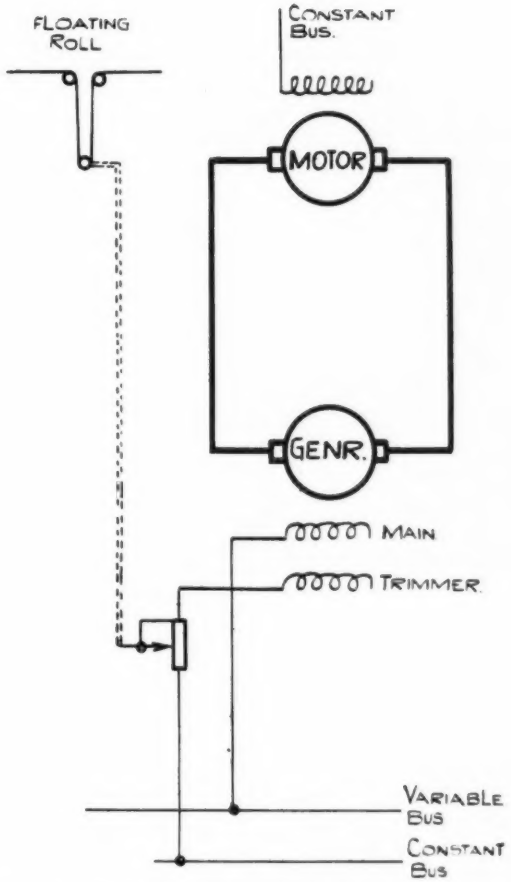


Fig. 16.—Snub rolls and drying drums controlled by floating roll rheostat

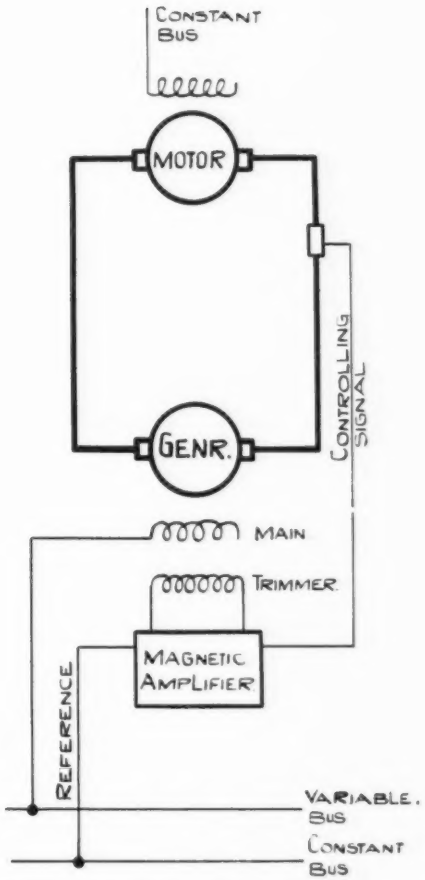


Fig. 17.—Tension control of pull rolls by magnetic amplifier control of generator excitation

The twin calenders, in tandem, coat the fabric first on one side and then on the other, thus obtaining double coating in one continuous operation.

Correct tensioning of the fabric during calendering is important, and this is provided by an air-loaded tension roll between the calenders and by tension rolls on the other sides of the calenders; the motors driving these rolls are controlled to maintain constant fabric tension. In the remainder of the train less tension is required and it is sufficient to provide only that necessary to maintain the fabric comfortably in contact with the drums and rolls and to provide correct wind-up tension.

Moisture content is removed from the fabric by passing it over the steam heated drums before calendering, and over the internally water-cooled drums after the double coating process, to dissipate some of the heat generated during calendering.

In order that the calenders may run continuously, fabric is stored in the air-loaded festoon at the let-off ; this is taken by the train when the let-off unit is stopped for splicing on a new roll. The let-off unit is afterwards automatically over-speeded to refill the storage festoon. Likewise, when the wind-up unit is stopped for roll changing, the

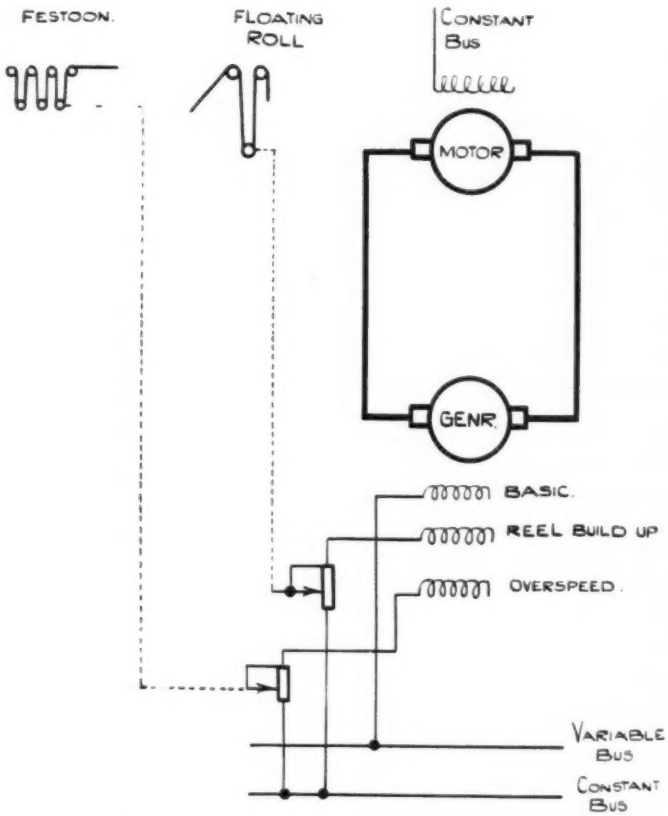


Fig. 18.—Wind-up control providing automatic reel build-up and overspeed

fabric fills into the festoon which is afterwards emptied again by automatically overspeeding the wind-up unit upon restarting.

Control Scheme

The extensive electrical control scheme comprises all the necessary contactors, relays, magnetic amplifiers, rheostats, limit switches etc., which are mainly accommodated in a multi-panel cubicle type control board. This is situated in the control room as shown in Fig. 11. Also accommodated in the control room are generators providing the variable voltage supplies for all the auxiliary motors in the calender train. These are grouped to form motor-generator sets and are driven by 415 volt 3-phase 50 cycles squirrel-cage induction motors at constant speed.

The two calender generators and the 6,600 volt 3-phase 50 cycles synchronous driving motor are situated near the calender train and are shown in Fig. 12.

Control of the train is carried out from the control desk shown in Fig. 13 and located between the two calenders.

As the process operating speed is critical, it is usual to provide the calender motors with constant speed holding equipment. By reason of the large power ratio between the calender and auxiliary motors, the speeds of the auxiliary motors will then adjust themselves accordingly.

In Fig. 14 the calender speed control scheme shows the generator field being supplied by the output of the magnetic amplifier. A voltage reference which is proportional to the basic train speed, and a tacho-generator signal which is proportional to motor speed, are fed to control windings on the magnetic amplifier, the difference being amplified to provide the necessary power output to the generator field. The motor speed is therefore proportional to the generator voltage, magnetic amplifier output, and difference between reference and signal voltage, a comparison of the latter being shown in Fig. 15. The system will automatically compensate for motor speed variations at a fixed reference setting.

A rheostat coupled to the floating roll between the calenders serves to adjust the speed of No. 2 calender, thus ensuring speed matching between the two calenders.

Due to variable expansions in the fabric it is not possible to match the speeds of all the drives precisely, but various means are provided for making automatic speed-trimming adjustments of the auxiliary drives.

The following are the basic methods used to ensure speed matching of the auxiliaries to the calenders and in providing the required fabric tension.

(*a*) A floating air-loaded roll in the fabric run has a deflection proportional to speed difference, and this is used to operate a rheostat as shown in Fig. 16 to control a trimmer field on the drying and cooling drums, thus matching the speeds of these drives to the tension pull rolls.

(*b*) The main field of the tension pull rolls generator is fed from the variable voltage busbar as in (*a*), and a trimming field is provided fed from a magnetic amplifier as shown in Fig. 17 to maintain motor current, torque and fabric tension constant. A signal proportional to the motor current fed to a magnetic amplifier winding opposes the fixed ampere-turns of a reference winding, and any difference results in output to the trimmer field either to aid or oppose the main field and thus correct for tension variations due to load changes.

It will be appreciated that the speed of the wind-up reel must be automatically decreased as the reel builds up, the principle being shown in Fig. 18. A separate generator field is supplied from a rheostat coupled to the festoon, providing an overspeed when the festoon is full and reducing the amount of overspeed as the festoon empties. A similar rheostat is provided on the let-off festoon to overspeed the let-off pull rolls when the festoon is empty. The let-off unit and festoon are shown on pages 24 and 25, as seen when looking along the train towards the No. 1 calender.

Emergency Stopping

There are vulnerable points throughout the train where injury to operators might occur, in particular at the calender rolls. In view of this it is possible to bring the whole train rapidly to rest, and a trip wire running the whole length of the train is provided for this purpose.

From the time of operation of the trip switch at maximum fabric speed, the fabric travels a distance to standstill not exceeding that laid down in the safety requirements. To achieve this, special consideration must be given to the design of satisfactory electrical and mechanical braking systems.

A combination of dynamic and regenerative braking is used for the calender motors, as shown in Fig. 19, and for the auxiliary motors where stopping is easier due to lower inertias, dynamic braking is used together with mechanical holding brakes. Since the largest portion of the inertia of the calender unit as a whole is in the driving motor, it is essential to provide low inertia motors.

The 'English Electric' Mill-type motor is particularly suitable for this duty, being of small diameter, and its very robust construction enables it to withstand the severe braking stresses imposed. Fig. 20 shows one of two such motors driving the main calenders.

When emergency stopping is initiated, the generator field contactor is de-energised to allow decay of the field through a non-linear resistor

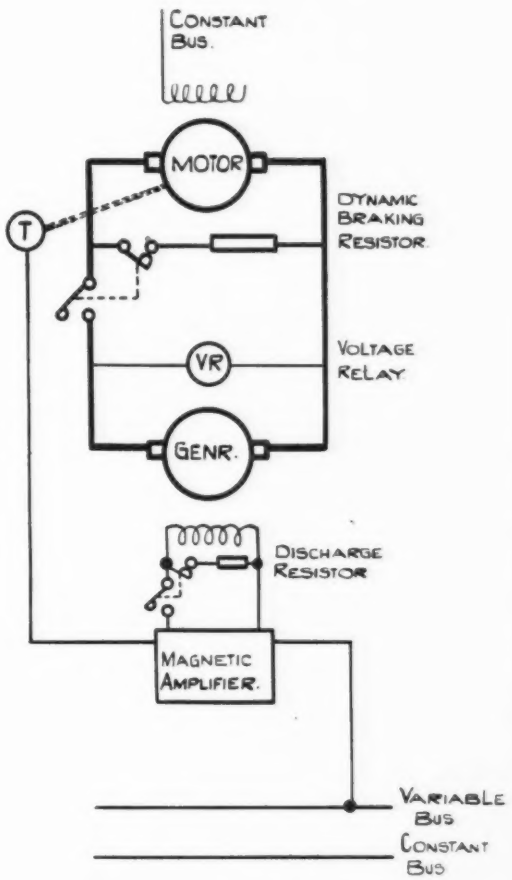


Fig. 19.—Electrical braking scheme for calender motor

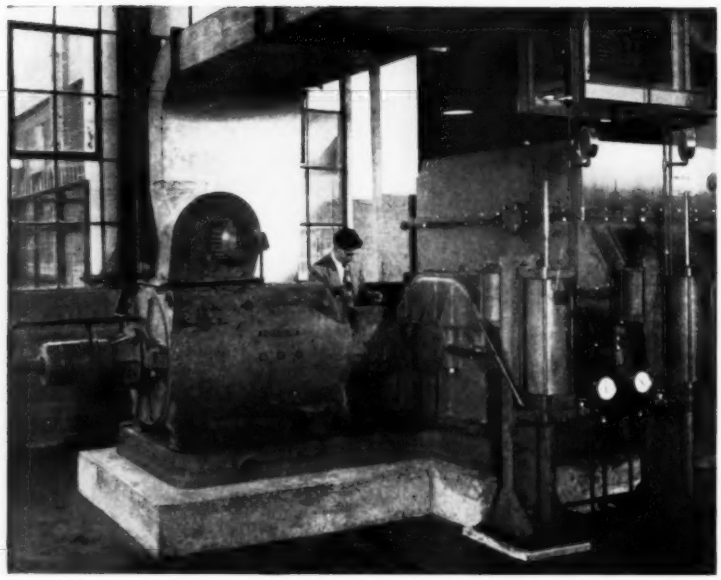


Fig. 20.—One of two 300 h.p. 1,200 r.p.m. 500 volts D.C. motors, of the 'English Electric' forced ventilated variable speed mill-type, each driving a Bridge three-roll calender through a reduction gear and flexible coupling. The pull-rolls motor can be seen in the top right-hand corner

giving a fast discharge. Simultaneously, reversal of motor current takes place establishing regenerative braking torque. At a pre-determined generator voltage, a calibrated relay initiates dynamic braking which takes over from regenerative braking to complete the stopping sequence.

The chart reproduced in Fig. 21 shows the emergency stopping characteristics for the 300 h.p. 1,200 r.p.m. 500 volts low-inertia motor driving the three-roll calender. The control gear operating time-interval from the point of operation of the trip switch to establishment of braking torque by reversal of motor current can be seen to be extremely small.

The circuits associated with the emergency stopping are designed so that the contactors and relays are de-energised to effect braking, thus

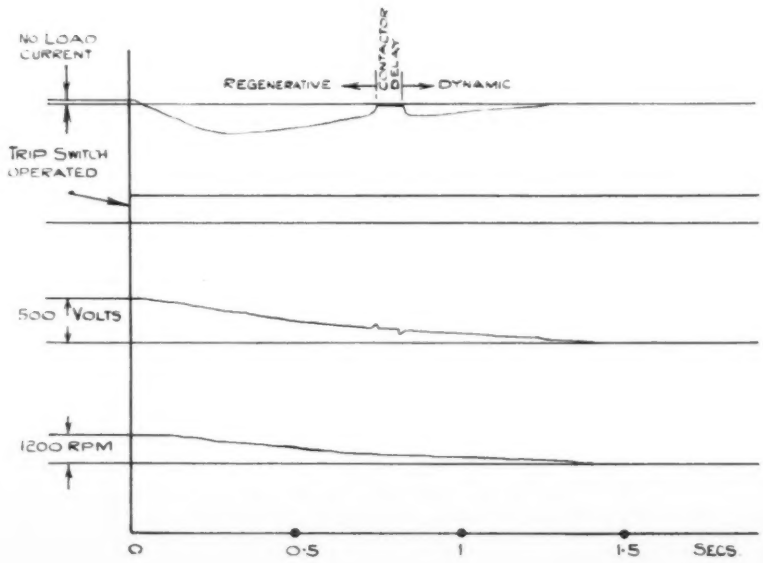


Fig. 21. Emergency stopping characteristic for a 300 h.p. 1,200 r.p.m. 500 volts low-inertia motor driving a three-roll calender

ensuring that an operating-coil failure does not fail to produce braking.

Conclusion

Throughout this article an endeavour has been made to show the relationship between special electric drives, the site conditions, the requirements of increased production, high product standards and safety of personnel.

The main points to be considered for mill and mixer drives are the load characteristics, the presence of carbon black in the atmosphere and, for mills, the safety of the operators.

Careful choice of motors is essential, and control gear, whilst not of a complex nature, should be sited away from the process. The inherent operating time for control circuits is important on mills.

The calender train co-ordinates a number of separate processes into a continuous high-speed unit, and the control scheme makes a big contribution towards the rapid production of tyre ply of consistently high quality. Modern control schemes of the type described are a good answer to the demand for a better product at lower cost.

Acknowledgments

The authors wish to thank the following Companies for permission to publish the photographs in this article :

The Goodyear Tyre and Rubber Company (Great Britain) Limited.

David Bridge and Company Limited.

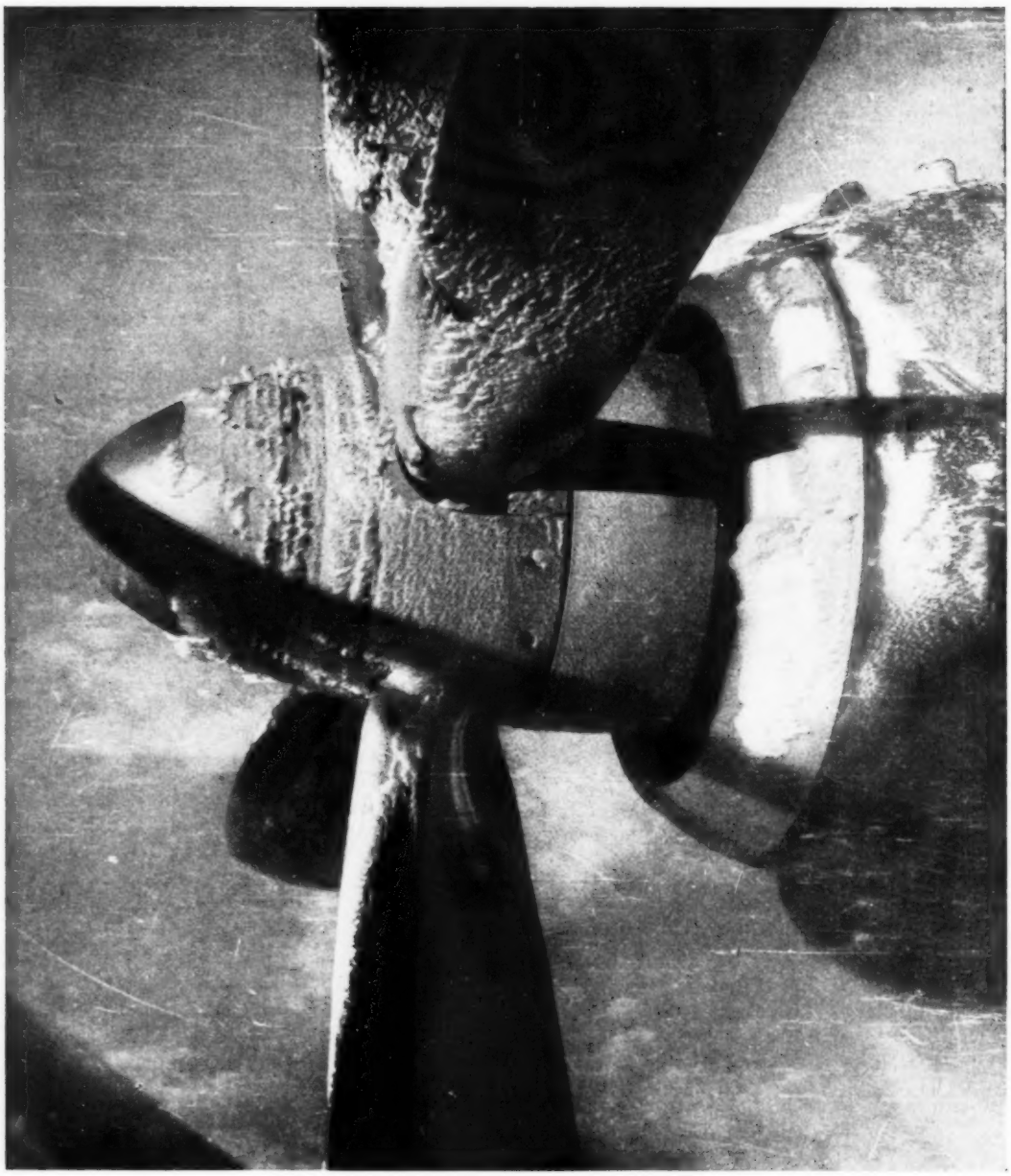


Fig. 1.—*An Eland engine during icing tests. The Spraymat anti-icing has kept the engine air intake lip clear; the cyclic de-icing is clearing the spinner nose*

The Napier Icing Research and Flight Test Organisation

THE NAPIER ICING RESEARCH ORGANISATION has been in operation for more than ten years. During this period, the increased speed, altitude and all-weather operation of aircraft has magnified the problems of icing. In common with the rest of the industry the Company has had to overcome these problems, and the scope of the facilities now available are a measure of the intensive research carried out, from the basic causes and types of ice formation to its prevention and dispersal.

Close collaboration is maintained with many research organisations in Great Britain, the United States of America, and Canada. Their findings are integrated with those of the Napier Organisation to form a very complete fund of knowledge.

The Napier Company is now in a position to offer the facilities and experience of its Icing Research Organisation to members of the aircraft industry, or of any other industry, who may have problems caused by the accretion of ice or the effect of low temperatures on engine intakes or structures.

Equipment includes flight test aircraft and an icing wind tunnel, both able to produce their own closely controlled simulated icing conditions at any time.

The principal advantages of the Organisation, are :—

(1) Delays in flight proving programmes due to absence of natural icing conditions are obviated.

(2) Expensive delays in development and need to redesign are avoided, as system and component proving may proceed in parallel with the construction of the prototype aircraft.

Fig. 2.
A Lincoln de-icing research aircraft

(3) Erroneous results due to difficulties in measuring the transient conditions of natural icing are eliminated.

Preliminary assessments of de-icing and anti-icing systems intended for new aircraft can be provided and proof of the systems can be made by testing representative components either in the icing wind tunnel or in flight. Thus the prototype aircraft can go forward for development and airworthiness trials with the systems working and to a large extent proved. The consequent saving of time and cost is very great.

PRINCIPLES OF ICING FLIGHT TESTS

Icing Severity Standards

Basically, there are three forms of icing to be considered, particularly with respect to engine performance and associated with :—

(*a*) Supercooled water droplets.
(*b*) Ice crystals.
(*c*) A mixture, in varying degrees, of water droplets and ice crystals.

Aircraft icing may also be associated with an almost infinite variety of altitude, airspeed, ambient temperature, water concentration, droplet size and duration of encounter.

It has been necessary therefore, for design purposes, to declare a standard of icing conditions. This does not presume to represent conditions known to exist but is rather an arbitrary standard which is accepted and understood by the aircraft industry and the certifying authority. As fresh data and experience become available so the severity standard may be modified. The standards are laid down in the appropriate sections of British Civil Airworthiness Regulations and the American Civil Airworthiness Authority Regulations.

Clearly it is not practical to demonstrate an aeroplane anti-icing system in all icing conditions likely to be met. Credit is therefore given by the certifying authority for demonstrations made in conditions considered to be severe based on the current severity standard and on experience with other aircraft types.

Demonstrating Suitability

In the flight testing and developing of ice protection systems, one of the principal difficulties encountered is that of finding natural icing conditions sufficiently uniform through which to fly the test aircraft. The chances of obtaining the right conditions near to the test aircraft and at a time when the test aircraft is serviceable are also slight ; probably one in 300 flying days at Luton, where the Napier Flight Development Establishment is situated. Natural cloud severity must also be measured, but reliable equipment for this does not at present exist.

Because of this it has been found more profitable not to seek natural conditions but instead to fly in clear air, at temperatures below 0°C, while spraying a test surface from a water spray rake fitted to a test aircraft.

Such an aircraft may conveniently and economically be a specially-adapted general purpose aircraft, fitted with special test equipment and the means for readily testing a variety of aerofoil types. A Lincoln is now used for this purpose by the Napier Company.

Simulating Natural Conditions

It is essential to prove that the simulated conditions are closely related to the natural conditions that will give the severity of ice accretion specified for test purposes. This requires correct simulation of the several factors noted previously, together with aerofoil incidence and sweepback, etc.

Altitude, airspeed, ambient temperature and duration of encounter are readily measured with standard instruments. The techniques for meeting other factors are noted briefly below.

(a) *Droplet Size*

Napier-developed spray nozzles are calibrated to produce droplets to the sizes and spectra specified in the various airworthiness standards. Sampling equipment provides a means of checking these requirements in flight.

(b) *Water Concentration and Spray Distribution*

These are readily determined from a knowledge of the spray area, and Napier experience enables uneven concentration and distribution within the spray area to be avoided.

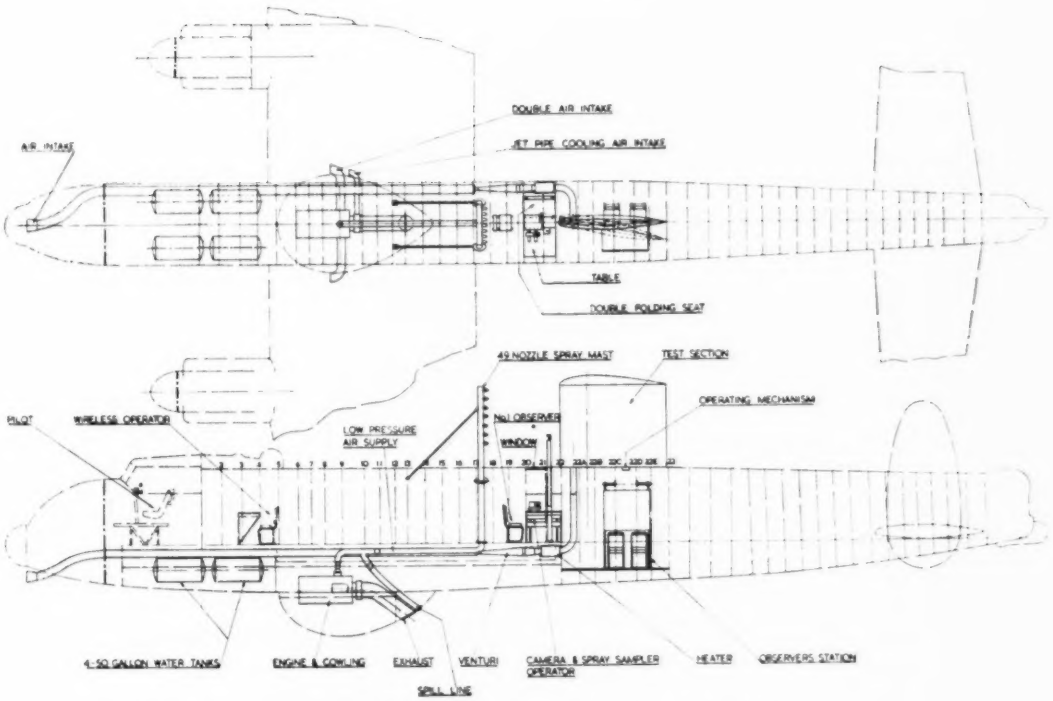


Fig. 3.—De-icing installation in Lincoln Mk.2 RF.342

(c) *Section Attitude*

The effective section incidence, dihedral or sweepback will not necessarily be that indicated, taking into account the line of flight and attitude of the aeroplane.

It is necessary to incorporate within the test section surface-pressure measuring points which will permit the determination of pressure distribution. It is then possible to determine the setting which will give a pressure distribution similar to that of the basic aeroplane.

FLIGHT TEST AIRCRAFT

The Napier Company has available a Lincoln aircraft converted for use as a ' flying laboratory ' on de-icing research (Figs. 2 and 3). The aircraft has been completely equipped for this work and provision is made for a wide range of aerofoil sections to be mounted above the fuselage so that the ice forming characteristics can be evaluated.

Externally the aircraft is similar to an earlier Lincoln converted by Napier to evaluate the ice protection system employed on the Blackburn Beverley. That is to say, a tailplane or wing leading edge specimen is mounted vertically on the fuselage, and in front of this test piece is a 49 nozzle spray grid (Fig. 4).

The spray grid is supplied with water under pressure from four 50 gallon bomb bay tanks. The wing aerofoil section is pivoted on a vertical axis to move through an angle-of-attack range of about 17°.

A Blackburn Turbomeca Palouste 3 air compressor unit, installed in the bomb bay, supplies air for the blast atomisation at the spray nozzles.

Hot air for anti-icing test sections is taken from a ram intake in the nose of the aircraft, passed through electrical heaters capable of dissipating a maximum of 70 kVA, and then ducted to the test section. For testing electrical de-icing systems, 80 kVA is available.

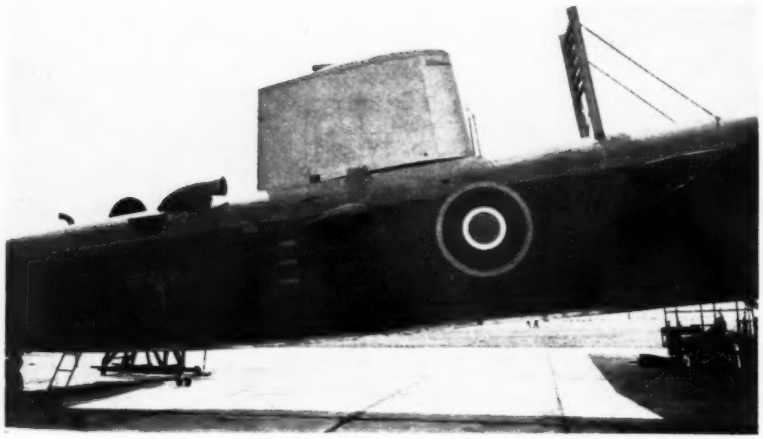


Fig. 4.— Equipment mounted on a Lincoln. (Right to left) spraymast, ice detector head, spray sampler, test section and air intake to hot air combustion heater

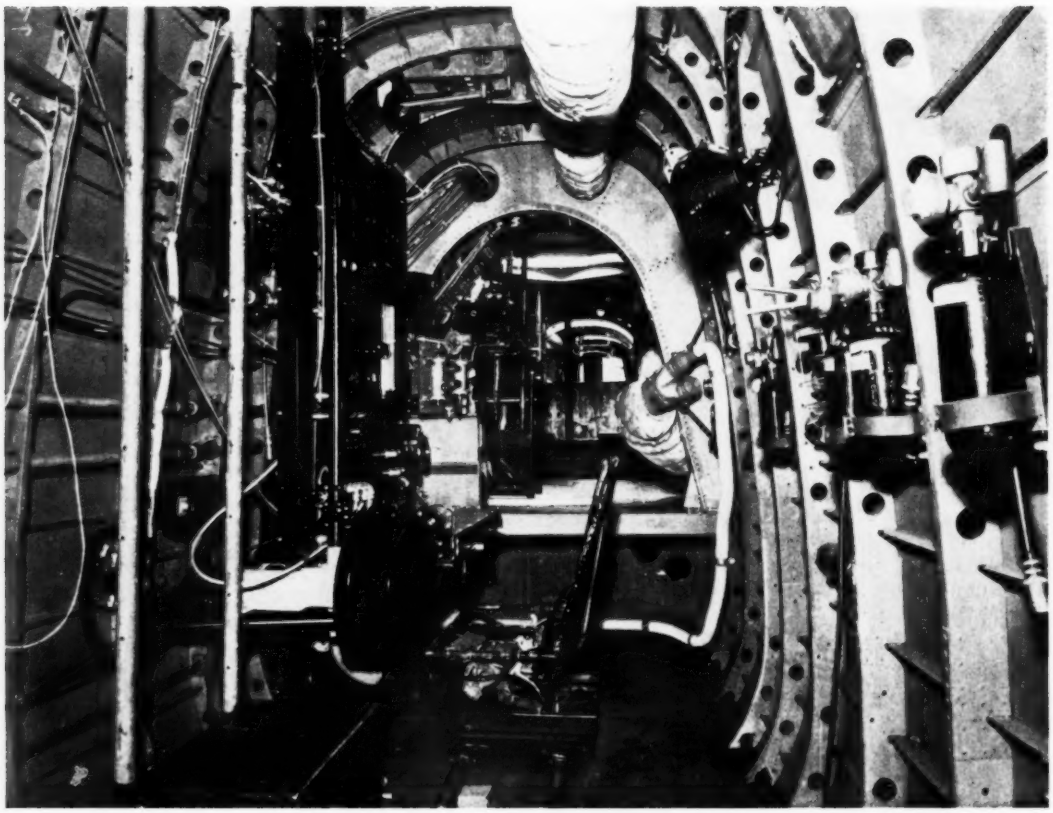


Fig. 5.—Observer station in a de-icing research Lincoln. The spray sampling equipment is on the higher level

The method of attachment of each aerofoil test section is similar to permit ready interchangeability, but the leading-edge structure incorporating the heating system is made representative of the aircraft on which the section is used. Provision is made in the construction of the section for measurement of surface temperature, gas temperature and gas pressure.

Instrumentation

Internally, a large panel at the observer station (Fig. 5) carries a complete range of instruments to record the water flow rate, water temperature, air speed, air temperature, etc., and forward of the observer station is comprehensive equipment for obtaining and photographing the spray droplet samples.

Provision is made for the following measurements to be taken potentiometrically with a Honeywell Brown "Electronik" self-balancing potentiometric indicator :—

Ten aerofoil surface temperatures.

Ambient air temperature.

Frost point mirror hygrometer temperature.

This instrument has multi-channel selection switching for up to 24 thermocouples of two combinations, and offers the advantage that individual calibrations on each thermocouple circuit are unnecessary, at the same time possessing an accuracy of measurement much superior to the conventional type of dial indicator.

Technical Data

Test Section (typical)

Chord	9 ft
Span	7 ft
Incidence range ..	17°

Ice Simulation System

Spray grid	49 nozzles arranged 7 × 7
Maximum flow ..	147 gal per hour
Cloud area	7·3 sq ft
Water carried ..	200 gal
Atomising air pressure	45 p.s.i.g.

Grids giving other spray patterns and flows can be fitted as required.

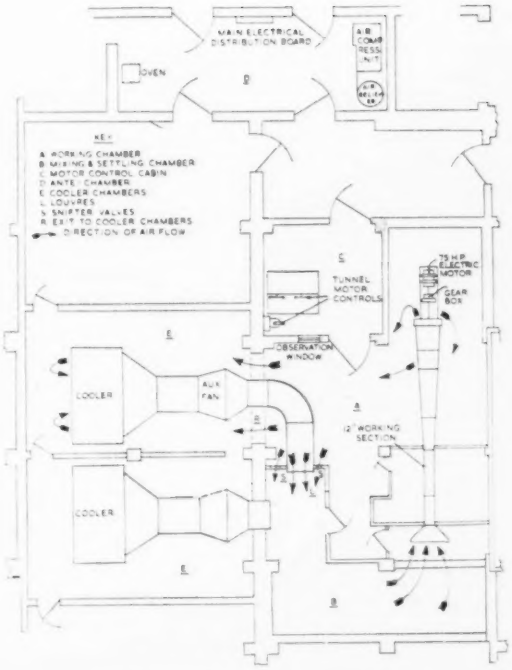


Fig. 6.—General layout of low temperature laboratory at Artington, Surrey

Hot Air Supply

Electrical heaters ..	70 kVA total	
Typical performance :—		
Inlet temperature	0°C	−20°C
Air flow	39 lb/min	39 lb/min
Heater input (total)	57 kW	59 kW
Maximum temperature rise ..	192°C	205°C

Aircraft Performance (typical)

Speed	247 knots (true air speed)
Altitude	30,000 ft
Temperature ..	−40°C to −50°C

(Varying according to weight and drag)

Flight Testing

The present Lincoln is the latest of several aircraft which have been used by the Napier Company in its many icing research programmes, and the comprehensive equipment installed has been chosen and developed as a result of this previous experience. This equipment, handled by

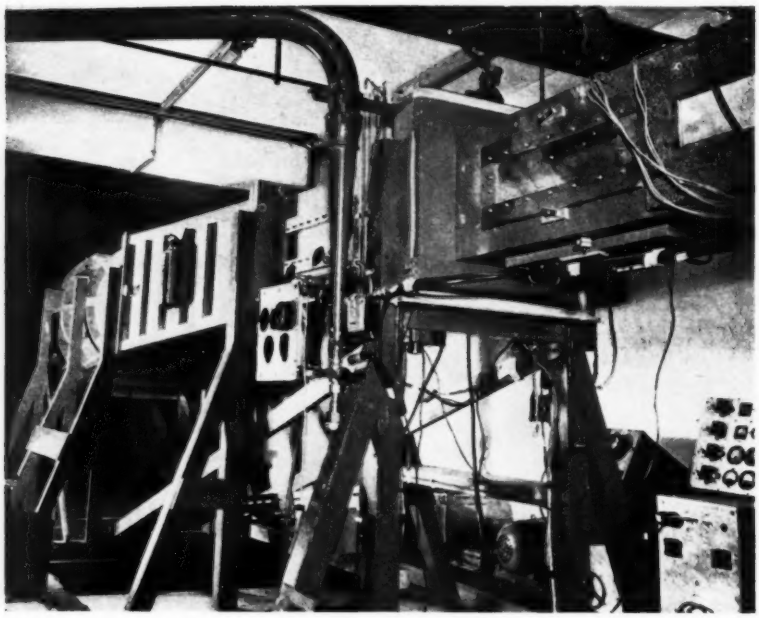


Fig. 7.
The Artington wind tunnel

competent observers, is sufficient to prove compliance with all icing severity standards, thus showing a tremendous saving in aircraft manufacturers' flight test programmes.

The following outline of a de-icing flight test programme is typical of that required to prove, in intermittent and maximum icing conditions, the hot air de-icing system of a large jet airliner.

After installation of the test section :—

Stage 1. Proof flights to include :

(*a*) Pilot's handling checks.
(*b*) Instrumentation checks.
(*c*) Flight performance of test system and equipment.

Stage 2. Preliminary icing checks which will entail :

(*a*) Surface pressure measurement.
(*b*) Dry air levels with known heat input.
(*c*) Determination of the critical nature of I.A.S.,† incidence and droplet size.

† *Indicated Air Speed.*

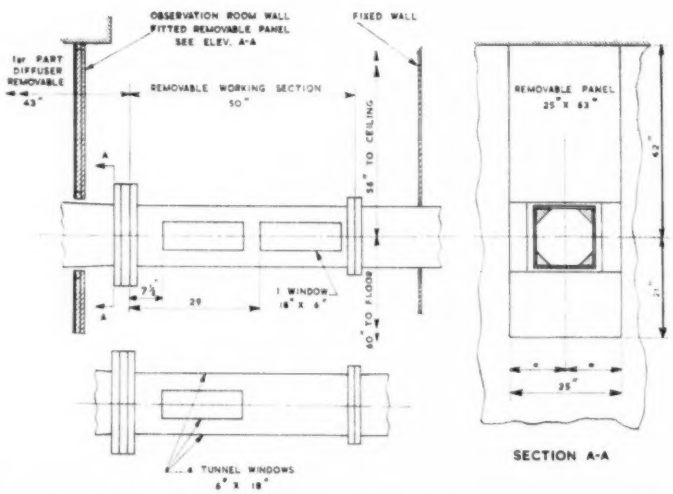


Fig. 8.—Detail of working section showing accommodation available for large rigs

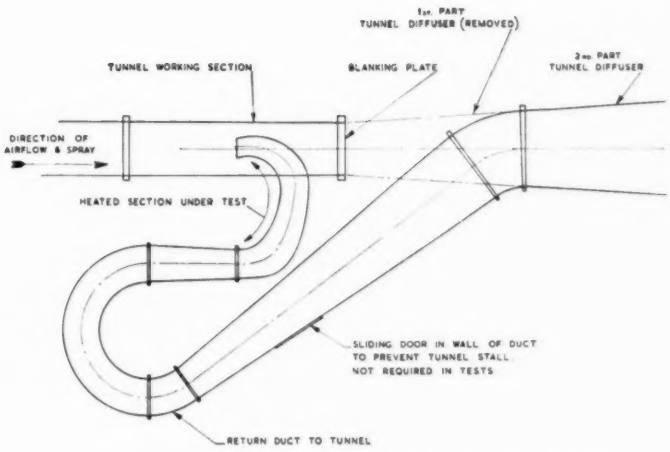


Fig. 9.—General layout of rig for Proteus engine duct

(*d*) ' Breakdown ' tests to provide guidance for icing tests proper.

Stage 3. Main test programme to include :

(*a*) Demonstration to Continuous Maximum Severity standard at a sufficient number of temperature conditions.
Determination of heating intensities required for adequate performance.

(*b*) Demonstration over the range of aircraft operating altitude/temperature, i.e. at say (1) I.C.A.N.‡ +25°C, and (2) I.C.A.N. −5°C.

(*c*) Demonstration at Climb, Cruise and Descent configuration.

Stage 4. Further data on :

(*a*) Reduced heat performance.

(*b*) Operation at Intermittent Maximum Severity with heat input found necessary at 3 (*a*).

(*c*) Operation at Intermittent Maximum Severity with greater heat input if performance at 4(*b*) is not acceptable.

It is estimated that between 35 and 50 flying hours are required to complete a programme of this nature. As it can be undertaken at an early stage of the aircraft construction, and whilst associated equipment is being tested by other Napier facilities, the total saving of time and cost when the aircraft undertakes its development trials can be very great indeed.

‡ *International Committee on Air Navigation.*

THE NAPIER ICING WIND TUNNEL

The Napier icing wind tunnel and low temperature laboratory (Fig. 6) is situated at Artington in Surrey and forms a very valuable part of the Company's icing research facilities.

The wind tunnel itself (Fig. 7) is of the open return suction type powered by a 75 h.p. electrically driven fan. Speeds of 350 ft/sec are obtained when using the standard 12 inch square tunnel section, with tunnel temperatures down to −38°C.

Provision has been made to accommodate working sections of various sizes and shapes, enabling intake models and other ducts to be simulated. The standard 12 inch square section (Fig. 8) has removable windows in each wall to enable test pieces to be mounted and viewed from any of the four sides. Other non-standard working sections, including one for reverse flow ducting, are shown in Figs. 9 and 10.

Tunnel temperatures between +5°C and −30°C can be easily controlled to within ±1°C, and temperatures below −30°C are controllable to within ±4°C. This refrigeration is continuous, allowing prolonged test runs at any temperature.

Compressed air and water supplies, both filtered and fully metered, are available for operating a variety of spray mast configurations and for general purposes. A high-vacuum pump is also available for extracting tunnel air samples and other purposes.

Static cold chamber tests can also be carried out. A working space of 24 ft × 10 ft with a height of 8 ft is available in which temperatures down to −40°C can be obtained and the humidity controlled up to 100%.

Test Facilities

Comprehensive facilities are provided to enable

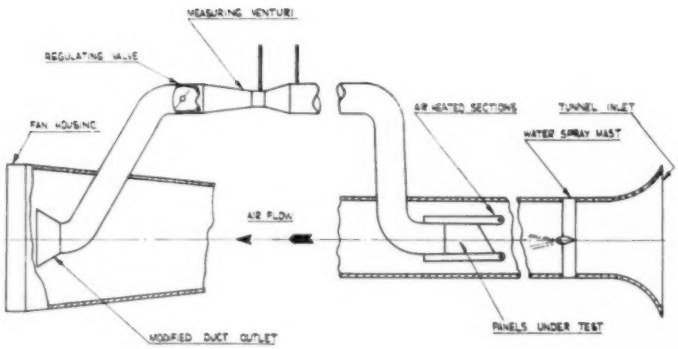


Fig. 10.—Bristol Proteus intake under test, showing method of inducing a controlled flow through intake

all aspects of ice formation and its removal to be studied. Test procedures have been developed which allow simulation of icing conditions to the severity standards specified by all airworthiness authorities.

Water concentrations up to 5 gm/m³ can be easily obtained for ice formation, and a 2 inch square area in the centre of the tunnel section has been very accurately calibrated for water contents up to 2·5 gm/m³, which is ideally suitable for the calibration of water content meters, etc.

A mean water droplet diameter of 20 microns or less can be obtained with water concentrations up to 2·5 gm/m³ at 350 ft/sec, using the standard single nozzle spray system. The spectrum of the spray (Fig. 11) is similar to natural cloud, a typical sample with a mean diameter by weight of 20 microns being shown in Fig. 12. This range can be extended to 5 gm/m³ by installing a multi-nozzle spray system which would also give accurate and even distribution over the full cross-section of the tunnel.

Apparatus is being developed to produce an evenly distributed cloud of ice crystals at the working section. These crystals are as similar to

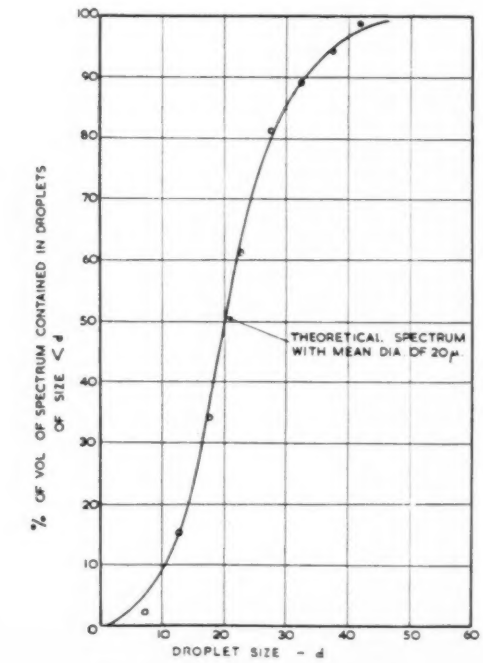


Fig. 11.—Typical droplet spectrum

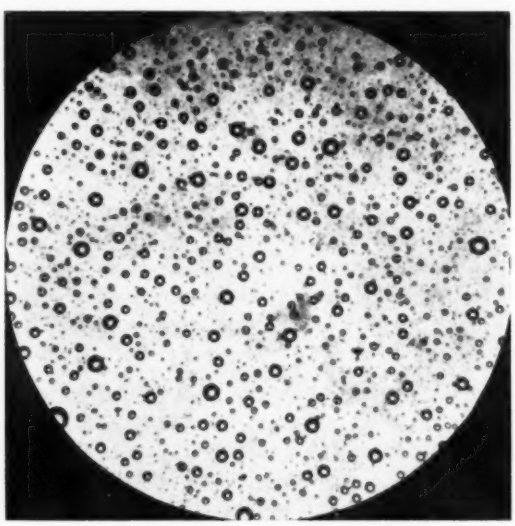


Fig. 12.—Typical droplet sample

those obtained in natural conditions as the present knowledge of these conditions will allow.

Instrumentation

Instrumentation is available for thermocouple and other temperature sensing devices together with all necessary pressure and flow metering equipment.

Equipment is provided for both still and cine photographic recording of test specimens in the working section. In addition, photomicrographic equipment is installed for recording water droplet and ice crystal specimens, etc.

Technical Summary

Tunnel Data

Airspeed	0 to 350 ft/sec (Fig. 13)
Temperature ..	+10°C to −38°C
Rating	Continuous
Temperature limits	+10°C to −30°C controllable to ±1°C. Below −30°C controllable to ±4°C
Standard working section :	
Cross-sectional area	12 in × 12 in less 3 in × 3 in triangular fillet in each corner
Length of removable section	50 in
Window cut-out size	6 in × 18 in

Icing Simulation Data

Supercooled Water

(*a*) Standard single air atomising nozzle :

Water concentration	0 to 2·5 gm/metre³ at 350 ft/sec
Droplet size ..	Down to less than 20 μ (50% volume median dia)

(*b*) Multi air atomising nozzles (can be installed if required) :

Water concentration.	0 to 5 gm/metre³ at 350 ft/sec
Droplet size ..	Down to less than 20 μ
Ice Crystals ..	Air atomising ice crystal nozzle (under development)

Air Supplies

Compressed Air ..	100 cu ft free air/min at 0 to 60 p.s.i.
Heated compressed air	Three separate air deliveries each incorporating a 1 kW heater
Vacuum	Kinney High Vacuum 110 cu ft/min

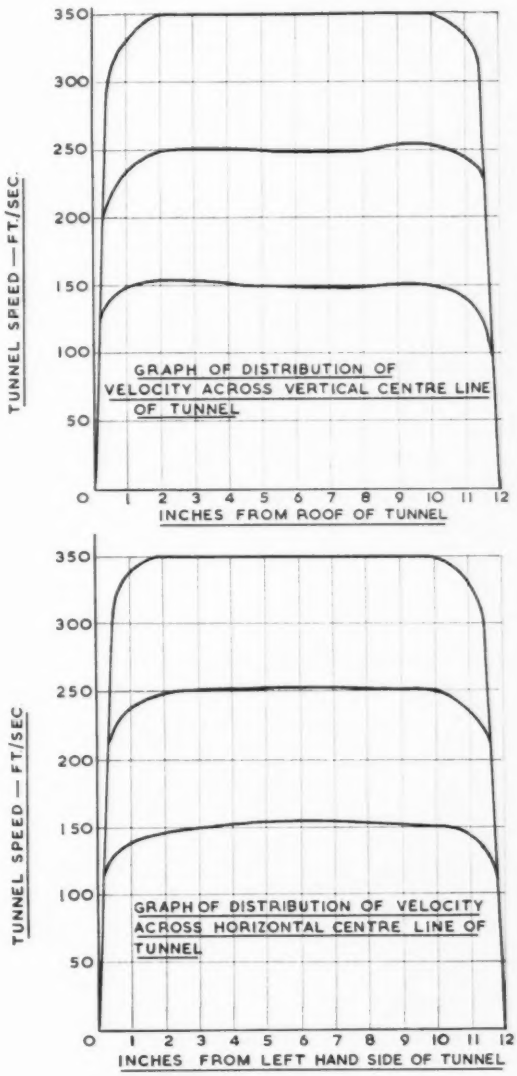


Fig. 13.—Velocity traverse of 12 inch section wind tunnel with maximum useful speed of 350 ft/sec

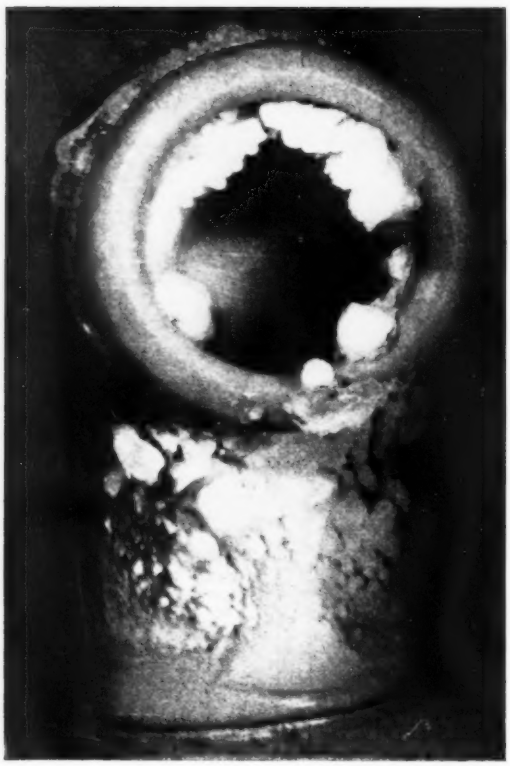


Fig. 14.—Blackburn Beverley combustion heater intake after 3¼ hours at −10°C and 0·6 gram/m³ water contents

Electrical Supplies

Input	.. ..	3-phase 50 cycles 400 volts at 300 amp
50 cycles A.C.	..	3 single-phase units, each 20 to 230 volts at 25 amp 1 single-phase unit, 0 to 230 volts at 8 amp
400 cycles A.C.	..	1 3-phase 1·2 kVA alternator at 208 line volts
D.C. supply..	..	0 to 110 volts at 5 amp 28 volts (batteries)

Humidity

Controllable up to 100%.

Static Cold Chamber

Unrestricted space ..		24 ft × 10 ft × 8 ft high
Access door..	..	4 ft × 6 ft 6 in
Temperature	..	+10°C to −40°C
Humidity ..	..	Up to 100%

Typical Test Cases

The tunnel is particularly suited for investigating the performance of various ice protection systems on small intakes, scale aerofoils and sections of engine intakes, etc., as the icing conditions required by airworthiness authorities both intermittent and continuous can be obtained in the tunnel for any length of time. Also, development is proceeding to enable a cloud of ice crystals or mixed conditions to be introduced into the tunnel and their effect on specimens assessed.

Typical examples of components which have undergone their tests are the Blackburn Beverley combustion heater intake (Fig. 14) and a section of the Bristol Proteus engine intake duct.

The tunnel has also proved invaluable for assessing the performance of, and calibrating, instruments and other devices for measuring or detecting icing parameters, such as ice detectors, water and crystal concentration meters and droplet sampling devices.

Investigations into the characteristics and further development of atomisers for the production of simulated icing conditions is also an ideal subject for the tunnel.

The range of icing conditions available makes the tunnel suitable for investigating the temperature gradients over heated surfaces under various degrees of cooling. In addition, the performance of temperature sensing elements, thermal cut-outs or complete thermostatic control systems can be accurately assessed.

SUPPORTING FACILITIES

Laboratories

The laboratory sections, taken together, form a self-contained group of development departments. Their function is both advisory and to carry out research into problems of applied chemistry and metallurgy.

Metallurgical Laboratories

There are three sections of the metallurgical

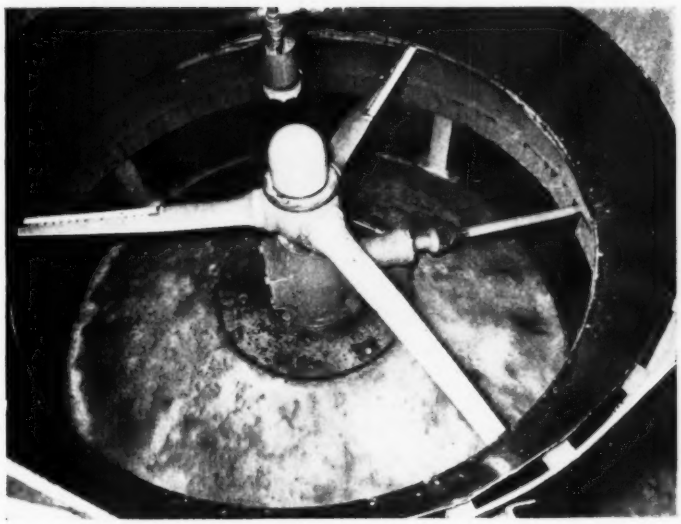


Fig. 15.—The rain erosion test rig

laboratories, the first dealing with physical metallurgy, the second with mechanical testing and the third with industrial radiology.

In the physical laboratory complete facilities exist for the staff to examine and report upon the structure of metals and possible faults in welds and components.

The mechanical testing laboratory is equipped to carry out physical tests in tension, compression, transverse bending, as well as Brinell and Vickers hardness tests and Izod impact tests.

The industrial radiology section carries out X-ray examinations of castings and forgings, using Marconi 250 kV X-ray apparatus.

Chemical Laboratories

The chemical laboratories are organised into four sections dealing with chemical analysis, electrochemistry (plating, protective coatings, etc.), plastics and organic chemistry, and physical chemistry.

In the analytical laboratory the examination of metallic materials is conducted by standard techniques, including colorimetric and polarographic methods. Exhaust gas analysis is undertaken, methods having been devised for taking samples in flight.

Work in the electro-chemical laboratory is largely concerned with investigations into processes for the deposition of metallic films on electrical conductors and non-conductors.

The plastics and organic chemistry laboratory is equipped for investigations into the suitability and development of various plastics for specialised applications. Prototype mouldings are made from synthetic rubbers and other materials.

All problems involving the accurate measurements of a particular chemical or physical property are referred to the physical chemistry laboratory.

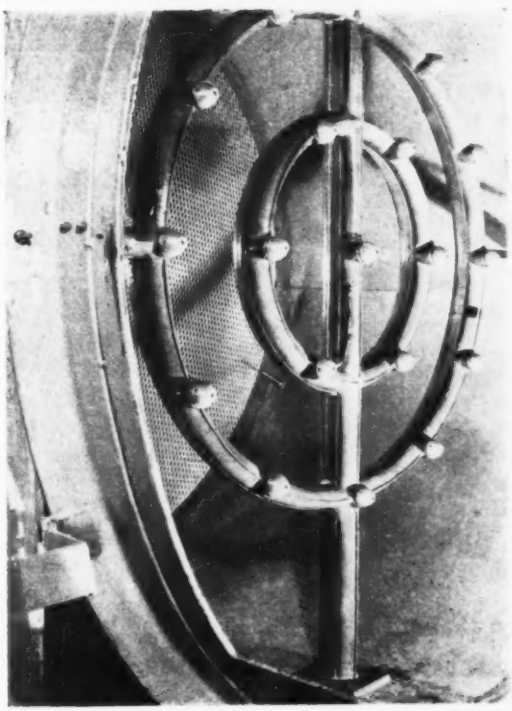


Fig. 16.—Sprayrake supplied to N.A.E., Canada

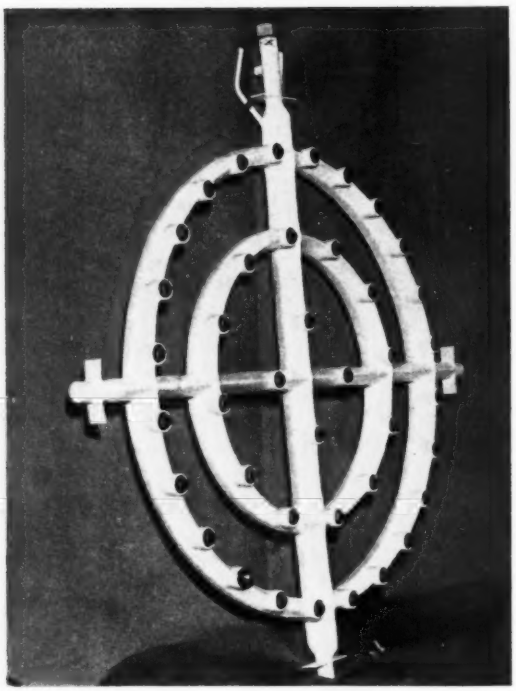


Fig. 17.—*40-nozzle mast supplied to a leading aircraft engine manufacturer*

Rain Erosion Test Rig

In the design of exterior components for high-speed aircraft the problem of rain erosion increases in severity with higher flight speeds and must therefore be considered when selecting materials or surface finishes. The Napier rain erosion test rig was primarily developed for testing materials used in the construction of de-icing surface heater mats, but can obviously be used for many similar purposes.

Erosion tests carried out under flight conditions are extremely expensive and present the difficulty of finding and measuring rain conditions of a regular severity for any length of time. The test rig, however, can produce a range of conditions varying in flight speeds and water concentration that can be prolonged for any duration or repeated whenever required. Flight speeds up to 910 ft/sec (Mach No. = ·81) at a rainfall of 3 inches per hour are the maximum conditions simulated by the test rig.

Equipment

The rain erosion test rig (Fig. 15) consists of a three-bladed propeller mounted vertically on a right-angle bevel drive gear-box, and driven by a V-8 engine through a layshaft and flexible couplings. Surrounding the propeller is a vertical tunnel which serves both as an air flow guide and a protective wall. The propeller blades are of constant section and have no twist, as they are specifically designed to accommodate test specimens in the form of overshoes which are attached to the leading edge of each blade. A water spray nozzle is mounted above the propeller and is designed to simulate rain conditions equivalent to a 3 inches per hour rainfall.

Adjacent to the propeller assembly is a small building to accommodate the power plant, the drive shafts between gear-box and engine being covered by sheet metal tunnels.

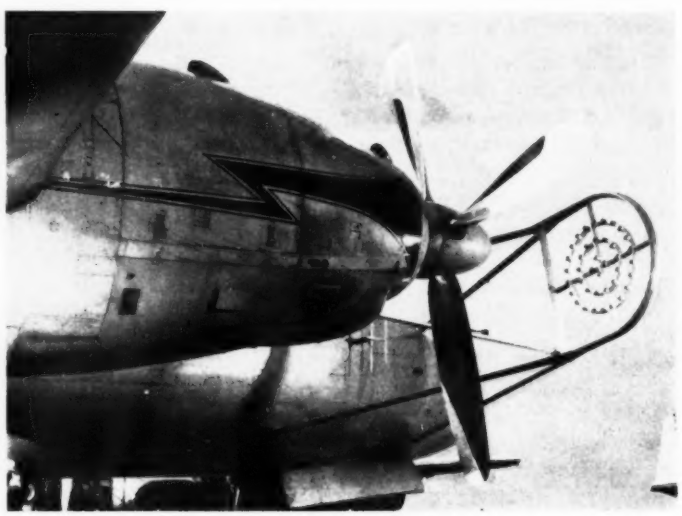


Fig. 18.—*Icing simulation equipment fitted to the Eland Varsity to prove the efficacy of the engine anti-icing systems*

Fig. 19.—A hand-held droplet sampling gun for use in the wind tunnel. The permanent aircraft installations operate in a similar manner

Data

Principal Dimensions :

Propeller diameter ..	6 ft 0 in
Test piece length ..	1 ft 6 in
Max. blade thickness over the test section length	0·60 in
Number of blades ..	3
Propeller blade settings	0°, 2°, 4°, 6°

Rain Simulator :

Water supply pressure	10 p.s.i. max.
Water spray nozzles —24	1 mm bore
Air supply pressure ..	30 p.s.i. max.
Rainfall equivalent ..	3 in per hr max.
Droplet size	2 mm

Propeller Speeds (Maximum) :

Propeller r.p.m. ..	Top gear 2900
Tip speed	910 ft/sec

Fig. 20.—An early ice simulation installation with the Naiad engine on test

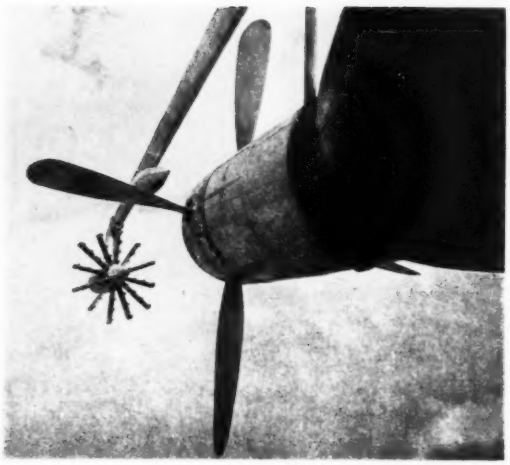


Fig. 21.—Detail of the Naiad de-icing installation. A camera was housed in the fairing on the sprayrake support arm

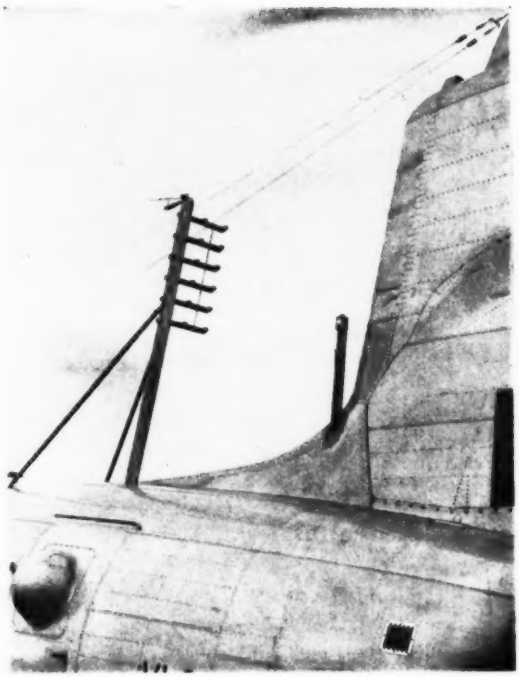


Fig. 23.—The spraymast, droplet sampler and fin-mounted test section on the Viking de-icing research aircraft

Design and Development

The Napier De-icing Engineering Department has considerable experience in solving icing simulation and ice protection problems.

The icing simulation spray nozzle used in all Napier icing research has been successfully developed and is in use both in Great Britain and abroad.

Many icing spray masts have been designed, manufactured and supplied for use in both ground test beds and flight installations. Fig. 16 shows a 19-nozzle mast installed in an icing duct in a

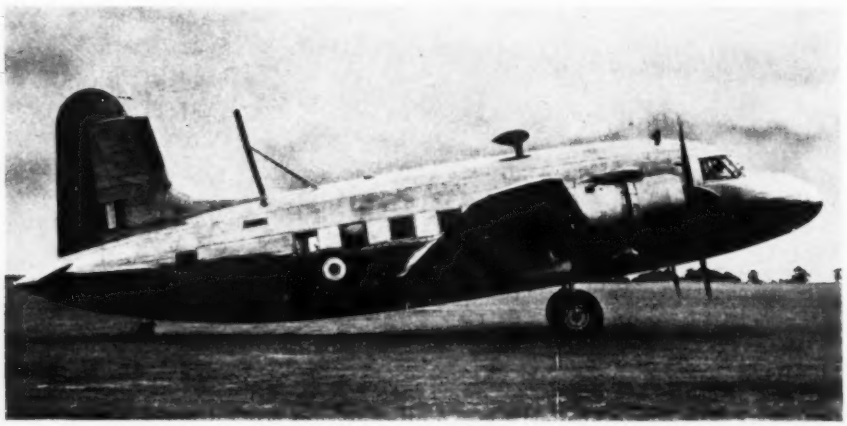


Fig. 22.—The Viking de-icing research aircraft

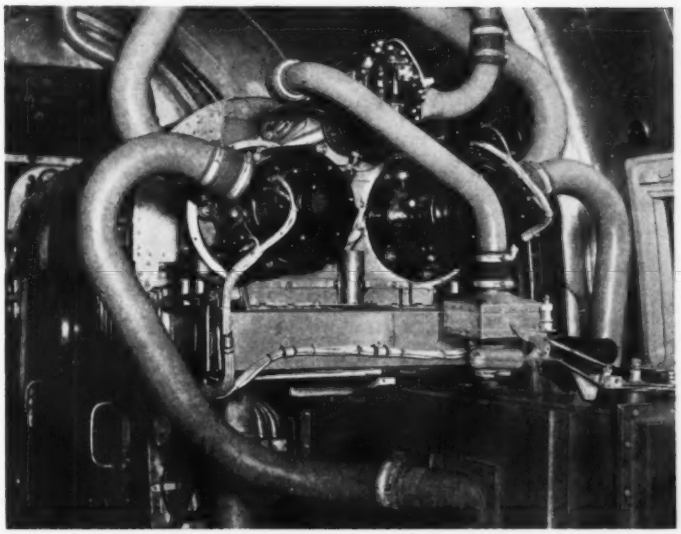


Fig. 24.—In the Viking a Gipsy Queen engine was used as an auxiliary power unit driving a generator and alternators. Later installations included a Marshall blower

Canadian engine test cell, and the 40-nozzle mast shown in Fig. 17 was supplied to a leading British aircraft engine manufacturer.

Complete icing simulation systems for use in flight or ground test beds have been designed and installed. Fig. 18 shows an installation on a Vickers Varsity aircraft for flight testing the Napier Eland engine in icing conditions.

One of the instruments successfully developed to ensure high standards of simulation is the Droplet Sampling Gun shown in Fig. 19. This apparatus propels a small oil-coated glass slide across a gap which is placed in the cloud or spray, and a sample of the water droplets is caught in the oil. The slide is then photographed through a microscope and the mean droplet size deduced. Water concentration meters and ice detectors have also been thoroughly investigated.

The same department is also responsible for the design and development of the Napier 'Spraymat' surface heater,* and deals with problems of heat transfer and test techniques including temperature measurement.

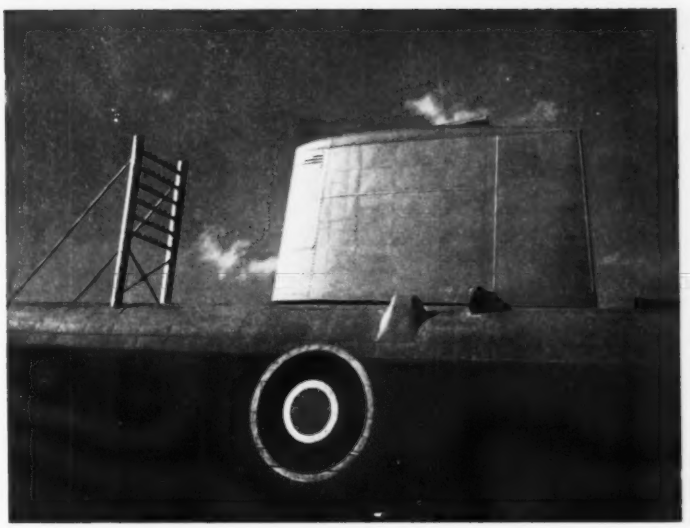


Fig. 25.—A test section with hot air leading edge de-icing mounted on a Lincoln

PAST FLIGHT EXPERIENCE

The illustrations in Figs. 20 to 26 show the scope of flight test work that has been carried out in the past. The Viking has now been retired but the Lincolns continue in service carrying out tests for the Ministry of Supply and various aircraft manufacturers.

Much of the success of Napier Spraymat electrical de-icing may be attributed to development work carried out on the Viking. Also, many of the techniques for measuring surface temperatures and

* *Described in the E. E. Journal, December 1954, Vol. 13, No. 8, p. 353.*

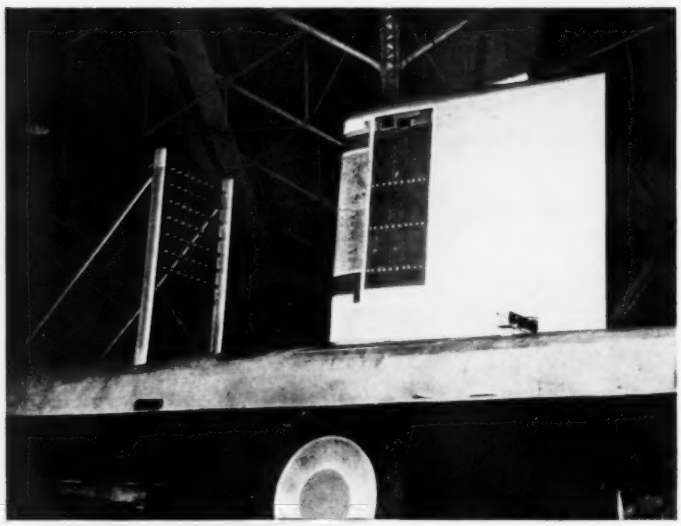


Fig. 26.—Hot gas leading edge test section with Napier Spraymat clearing fringe and run-back areas

droplet sizes, and handling ice simulation equipment and de-icing systems, were initiated and subsequently perfected during this period.

One of the many icing investigations carried out with the Viking was on representative wing and tail sections of the Bristol Britannia. The sections were fitted to an overshoe on the fin, and the hot gas anti-icing for the wings and electrical heater mats for the tailplane were proved.

The principal tests carried out on Lincoln aircraft have been for the Blackburn Beverley and the Comet 4A. As a result of the Beverley tests, clearance for flight in icing conditions was granted. The tests for the Comet are still proceeding but unrestricted clearance is expected shortly.

'CONSIDERATIONS IN THE DESIGN OF OUTDOOR HIGH VOLTAGE SUBSTATIONS'

REVISION OF TABLE VII

Table VII, giving sizes of flexible conductors, which appears on page 22 of the September 1957 issue of this Journal (Vol. 15, No. 3), should be revised to read as follows:—

Sectional Area square inches	Wire Diameter and Stranding	Current Rating amperes
0·15	19/·104	400
0·30	37/·104	600
0·40	37/·116	800
0·70	91/·104	1,200
1·10	91/·131	1,600